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TECHNICAL REPORT

Integrated Study of Seismic and Infrasonic Signals from Sources in Southern Siberia, Eastern Kazakhstan and Western China

October 2004

DSWA 01-97-C-0156

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14. ABSTRACT
Our Final Report has two parts. The first part is a draft of a paper, submitted for publication, entitled "A study of small magnitude seismic events during 1961-1989 on and near the Semipalatinsk Test Site, Kazakhstan." In this paper, we have estimated origin time and assigned magnitude for 31 previously undocumented underground nuclear tests and for 19 of these 31 have obtained locations based on seismic signals. The second part is a draft of a paper, submitted for publication, entitled "Infrasound Detection of Large Mining Blasts in Kazakstan." In this paper, we describe infrasonic observations recorded since October, 1997, at the Kurchatov Observatory in Kazakstan from large mining blasts in Kazakstan and Siberia.

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Preface

We thank Dr. Frode Ringdal of NORSAR and Dr. Yuri Kopnichev of CSE, who made considerable efforts to find detections and assign magnitudes for particular events reported in this paper. We also thank Dr. Bill Leith of the US Geological Survey, and Dr. Natalya Mikhailova of the National Nuclear Center of the Republic of Kazakhstan, for assistance in obtaining ground truth information. The Pure and Applied Geophysics version of this paper (April 2001) is publication number 6125 of the Lamont-Doherty Earth Observatory.

We thank the personnel of the Institute of Geophysical Research, National Nuclear Center, Kazakhstan, for their on-going efforts to maintain working instruments and to collect high quality geophysical data. David Lentrichia provided valuable technical assistance. The paper is Lamont-Doherty Earth Observatory contribution number 6292.

CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY →	BY →	TO GET
TO GET ←	BY ←	DIVIDE
angstrom	1.000 000 × E −10	meters (m)
atmosphere (normal)	1.013 25 × E +2	kilo pascal (kPa)
bar	1.000 000 × E +2	kilo pascal (kPa)
barn	1.000 000 × E −28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 × E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 × E −2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 × E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 × E −2	radian (rad)
degree Fahrenheit	$t_k = (t° f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 × E −19	joule (J)
erg	1.000 000 × E −7	joule (J)
erg/second	1.000 000 × E −7	watt (W)
foot	3.048 000 × E −1	meter (m)
foot–pound–force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 × E −3	meter^3 (m^3)
inch	2.540 000 × E −2	meter (m)
jerk	1.000 000 × E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 × E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 × E +3	kilo pascal (kPa)
ktap	1.000 000 × E +2	newton–second/m^2 (N–s/m^2)
micron	1.000 000 × E −6	meter (m)
mil	2.540 000 × E −5	meter (m)
mile (international)	1.609 344 × E +3	meter (m)
ounce	2.834 952 × E −2	kilogram (kg)
pound–force (lbs avoirdupois)	4.448 222	newton (N)
pound–force inch	1.129 848 × E −1	newton–meter (N-m)
pound–force/inch	1.751 268 × E +2	newton/meter (N/m)
pound–force/foot^2	4.788 026 × E −2	kilo pascal (kPa)
pound–force/incl^2 (psi)	6.894 757	kilo pascal (kPa)
pound–mass (lbm avoirdupois)	4.535 924 × E −1	kilogram (kg)
pound–mass–foot^2 (moment of inertia)	4.214 011 × E −2	kilogram–meter^2 (kg–m^2)
pound–mass/foot^3	1.601 846 × E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 × E −2	**Gray (Gy)
roentgen	2.579 760 × E −4	coulomb/kilogram (C/kg)
shake	1.000 000 × E −8	second (s)
slug	1.459 390 × E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333 22 × E −1	kilo pascal (kPa)

* The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
** The Gray (GY) is the SI unit of absorbed radiation.

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Section 1

Executive Summary

Our Final Report is in two parts. Part one is a text of a paper, submitted for publication, entitled "A study of small magnitude seismic events during 1961-1989 on and near the Semipalatinsk Test Site, Kazakhstan." In this paper, we have estimated the origin time and assigned magnitude for 31 previously undocumented underground nuclear tests (UNT) - and for 19 of these 31 have obtained locations based on seismic signals.

Part two is a text of a paper, submitted for publication, entitled "Infrasound Detection of Large Mining Blasts in Kazakhstan." In this paper, we describe infrasonic observations recorded since October 1997, at the Kurchatov Observatory in Kazakhstan from large mining blasts in Ekibastuz, Kazakhstan and Kuzbass and Abakan coal mining regions, Southwestern Siberia, Russia. We show that the synergistic use of seismic and infrasound signals greatly improve identification of the large mining blasts.

Section 2

A Study of Small Magnitude Seismic Events During 1961 – 1989 on and near the Semipalatinsk Test Site, Kazakhstan

2.1 Introduction.

It has been reported in recent official Russian publications (Mikhailov et al., 1996; USSR Nuclear Tests, 1997) that a total of 340 underground nuclear tests (UNTs) were carried out on the Semipalatinsk Test Site (STS) from 1961 to 1989. Only 279 of them had been included in previously published lists of Soviet underground nuclear explosions that included purportedly accurate origin times and locations (specifically, the lists contained in Bocharov et al., 1989, Ringdal et al., 1992; and Lilwall and Farthing, 1990). For eight of these 279 explosions, the magnitudes have not been available. So accurate epicenter parameters of 61 UNEs and the magnitudes of 69 UNEs appear not to have been given previously for this test site (STS).

The main goal of this paper is to estimate the origin time and location, and to assign the magnitude, for as many of the 69 hitherto undocumented UNTs at STS as possible. Our analysis is based principally upon seismic observations using regional stations located in Kazakhstan and elsewhere in Central Asia and southwest Siberia. We also evaluate the accuracy of locations for small UNTs at STS, as determined from regional seismic signals.

Besides underground nuclear explosions, our paper includes information about chemical explosions and earthquakes which have been detected on and near STS. Their parameters also were obtained from data of regional stations, and in some cases teleseismically. It is of interest, that some of these earthquakes and chemical explosions were included in some lists of Soviet underground nuclear explosions published in the West in the mid 1980s before Russian announcements about Soviet nuclear explosions were made beginning in 1992.

It is important to develop thorough documentation of all nuclear explosions, and especially for small explosions, as an aid in evaluating the detection and identification capability of monitoring stations. Of course, explosion monitoring in the present and the future will typically be done using stations that differ from those we have used to document small explosions at STS. Nevertheless our database of small explosions (chemical and nuclear), and nearby earthquakes, can provide guidance in estimating the capability of current networks, which can be expected to be better than the capability that was available for much of the period of active nuclear testing.

We shall use the distinction between a nuclear test and a nuclear explosion that was adopted in the revised protocol of 1990 for the Threshold Test Ban Treaty. Thus, a single underground nuclear test (UNT) can consist of a number of different underground nuclear explosions (UNEs) provided these are carried out within a time interval not exceeding 0.1 s and within an area delineated by a circle whose diameter is less than 2 km. Explosions with a time interval longer than 0.1 s, or a distance greater than 2 km, are counted as separate tests. We note that this distinction between UNTs and UNEs has been followed in official Russian documentation of the Soviet test program at STS, but with one exception, namely the nuclear test which was conducted at Degelen in a tunnel on January 30, 1974. (It consisted of three separate explosions. Western lists typically have given two tests separated by 4.4 seconds, but the official Russian

publication states, in translation, that "This test can be classified as one test with several subexplosions, however the time difference between subexplosions was more than 0.1 sec" and we have followed the Russian listing in counting this as one UNT.)

In the following sections, first we summarize the information from Russia officially available on STS UNTs. Second we describe the seismic data and methods of analysis that we have used in the study of small events. Third we describe our regional seismic detections of small events on and near STS, and their locations and magnitudes. Fourth we discuss the accuracy of their seismically-determined locations by making comparisons with ground truth information given by Leith (1998). Fifth we describe the agreement between seismically-estimated yields, and announced yield information; and we comment on detection thresholds for some different networks.

2.2 Summary of Available Official Information About UNTs From STS.

2.2.1 General information about all UNTs from STS.

The boundaries of the Semipalatinsk Test Site (STS) were defined and communicated to the US by the USSR in 1990 upon entry into force of the Threshold Test Ban Treaty. The information the USSR gave the US (now filed in the library of the US Department of State) consists of a set of 152 marker locations (latitude, longitude) on the perimeter of this test site, together with a map showing the boundary line from one marker to the next. As indicated in Figure 1, STS is about 100 km from east to west, and 150 km from north to south.

The 340 UNTs at STS listed by Mikhailov et al. (1996) and USSR Nuclear Tests (1997) were each associated with one of three sub-areas of the test site. Thus, 209 UNTs were in the Degelen sub-area, 105 at Balapan (sometimes referred to as Shagan), and 26 at Murzhik (sometimes referred to as Konystan). These explosions covered a wide range in yield, from less than 1 ton up to 165 kilotons (kt). Among 96 UNTs with magnitude *mb* less than 5.0, 84 were at Degelen, only 7 at Balapan, and 5 at Murzhik, so about 88% of the smaller yield events were in tunnels at Degelen.

The origin time and coordinates (latitude, longitude and depth) of STS UNTs have so far been announced by Soviet/Russian sources only for a group of 96 events that were conducted during a period from October 1961 to December 1972 (Bocharov et al., 1989; see also Vergino, 1989). Among these 96 UNTs, 6 were small and were not mentioned by Lilwall and Farthing (1990), or by Ringdal et al. (1992). With the official Russian announcements of 1996 – 1997 it became clear that 20 small magnitude tests at STS during this 1961 – 1972 time period had not been included in the list of Bocharov et al. (1989).

Location of 279 underground nuclear explosions on the Semipalatinsk Test Site

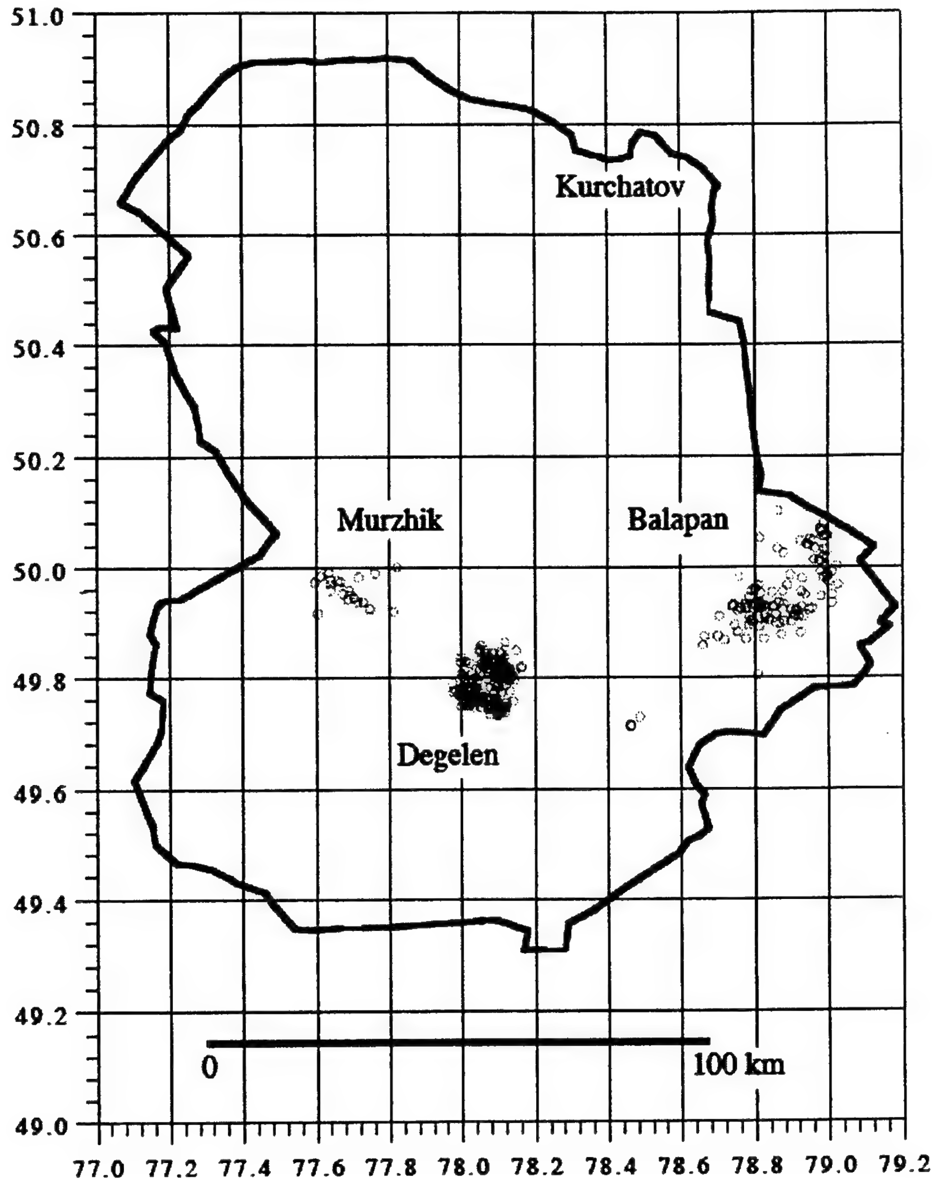


Figure 1. The boundary of the Semipalatinsk Test Site (STS) is shown, together with the location of 279 previously well-documented underground nuclear tests (UNTs) at this test site, in the three sub-areas of Degelen, Murzhik, and Balapan. The two UNTs shown near (49.7° N, 78.4° E) were tests of the capability to build canals, and are counted with the Murzhik events. The town of Kurchatov, headquarters for many activities on this test site, lies on the northeast.

In 1992, the Russian Federation declassified information about the dates on which Soviet UNTs had occurred, the number of tests and number of nuclear explosions carried out within one nuclear test, the yield range, the sub-area, and the purpose of these UNEs. However, the origin time, coordinates, and yield of most Soviet UNEs are still unavailable; and their seismic magnitudes, as determined from Soviet seismographic networks have not been announced, either by the network operated by scientists, known as ESSN, or by the military network, known as SSK.

A preliminary list of Soviet nuclear explosions was published by Gorin et al. (1994) in a scientific journal. Two official documents, Mikhailov et al. (1996) and USSR Nuclear Tests (1997), contain information about the date, name of the shaft or tunnel, purpose and yield range and identification numbers (from #1 to #715) for all 715 UNTs carried out by the Soviets, including for 340 UNTs conducted at the STS. In these latter two publications, yields were given for nuclear explosions conducted off the two weapon test sites at Novaya Zemlya and Semipalatinsk. Yields were also given for 27 UNTs at STS. For each of the remaining 313 STS UNTs, one of three yield ranges is given for the test: either, less than 1 ton (of TNT equivalent); or, from 1 ton to 20 kt; or, from 20 kt to 150 kt. Yields at STS are announced as greater than 150 kt, for only two tests: November 2, 1972 , with yield 165 kt and *mb* 6.16; and July 23, 1973, with yield range 150 – 1,500 kt and *mb* 6.17. These magnitudes were assigned by Ringdal et al. (1992) using the procedure of Lilwall et al. (1988) developed by the British Atomic Weapons Establishment, and we refer later to such magnitudes as *mb*(AWE). Both these tests took place prior to the date (March 31, 1976) given in the Threshold Test Ban Treaty, negotiated in 1974, for imposition of a 150 kt threshold.

Apart from the explosion locations given by Bocharov et al. (1989), Soviet and Russian publications have not listed UNT coordinates. But within the framework of Kazakhstan – US cooperation, coordinates of tunnel portals at Degelen have become available (Leith, 1998). Separately, the coordinates of Balapan shafts have been obtained through fieldwork conducted by the National Nuclear Centre of the Republic of Kazakhstan, and these locations are also now available (NNCRK, 1999). We use ground truth information in Tables below whenever these locations are available for specific explosions. When ground truth is absent (for example for chemical explosions) we give coordinates determined by seismological methods — which are shown to be quite accurate in a later section of this paper.

2.2.2 Small UNTs at STS previously undocumented by western seismologists in the open literature.

In this section we identify 61 UNTs at STS, out of the 340 now officially announced, for which accurate location information has not been given in openly available publications so far as we are aware; and we identify 69 for which accurate magnitude information has not been given. We assign each of these 69 UNTs to a category that indicates why their documentation has been poor (for example, low yield, or occurrence at the same time as another UNT). The following sections then report our own efforts to acquire and generate additional information, including locations and magnitudes, for as many of these 69 UNTs as possible.

Thus, the International Seismological Centre (ISC) has reported the seismically-determined

location and magnitudes of 271 UNTs at STS. Many researchers have carried out additional levels of analysis based upon ISC data for subsets of the STS events listed by the ISC. One of the largest such efforts, by the British Atomic Weapons Establishment (AWE), has applied the Joint Epicenter Determination method described by Douglas (1967) to ISC data, using several UNTs at STS as master events for which ground truth information was given by Bocharov et al. (1989) (and in English translation by Vergino, 1989). The AWE location estimates are given by Lilwall and Farthing (1990). AWE has also obtained maximum likelihood *mb*'s for 239 STS UNTs and has made them widely available on an informal basis. AWE mb's for 100 UNTs and one chemical explosion in the Balapan sub-area were published by Ringdal et al. (1992). An additional 8 UNTs, not mentioned by Lilwall and Farthing (1990) or Ringdal et al. (1992), are given with locations but not magnitudes by Bocharov et al. (1989) and Vergino (1989). On the basis of comparisons with SPOT locations (e.g., Thurber et al., 1993) and recently available ground truth information, we believe the AWE locations for 271 UNTs at STS, based on re-analysis of ISC data, are accurate to within a few km. In Figure 1, we show a map of the Semipalatinsk Test Site boundaries (as reported by the Soviet Union at the time of TTBT entry-into-force in 1990), together with the locations of 279 UNTs with coordinates given by the publications cited in this paragraph.

We can give three reasons why specific UNTs at STS were not included in the ISC and subsequent AWE listings. First, some UNTs have now been announced as having had yield less than 1 ton; such tests would generally be too small for either regional or teleseismic detection. Second, some UNTs were carried out at essentially the same time as another UNT and only one test was reported. Third, some UNTs have now been announced as having had yield greater than 1 ton, but they may still have been too weak for teleseismic detection with high confidence, given the networks in operation at the time. For these events, we can inquire as to the possibility of regional detection as discussed in the following sections. [Note that the papers by Lilwall and Farthing (1990), and Ringdal et al. (1992) were not intended as reports on teleseismic detection capability, and they characterized UNTs only for which the teleseismic data was of high quality. We comment below on papers by Sykes and Ruggi (1986, 1989) and Ringdal (1990) which reported the occurrence of several UNTs at STS additional to those listed by the ISC. Such detections were useful and important but they were not associated with accurate location estimates so we continue to include them in this paper with what we call "previously undocumented" events.]

Using information from the official Russian publications, we can tentatively see for each of these three reasons how many UNTs were not included in lists of events accurately located by seismic methods:

2.2.2.1 <u>Weak UNTs with yield Y announced as less than 1 ton.</u> This category consists of the 15 UNTs listed in Table 1. They would not be detected by standard instruments at distances more than 100 – 150 km. One of these small UNTs, with yield Y less than 1 ton, was carried out at Balapan (1973 Sep 20); the other 14 were carried out in the Degelen area.

Table 1. List of weak UNTs at STS with Y < 1 ton, which could not be detected even at typical regional distances.

N	Date	N	Date
1	1968 May 23	9	1979 Apr 10
2	1970 Feb 18	10	1979 Jun 12
3	1972 Apr 20	11	1980 Mar 14
4	1973 Sep 20	12	1981 Mar 25
5	1974 Feb 28	13	1981 Jun 04
6	1978 May 24	14	1981 Oct 16
7	1978 Jun 02	15	1983 Mar 11
8	1979 Mar 23		

2.2.2.2 Pairs of UNTs exploded simultaneously. This category is concerned with pairs of tests carried out within a short time interval, or even simultaneously, but with a spatial and/or temporal interval that requires them to be listed as different tests. In order to discuss specific UNTs with the same date, we use the number for each test that appears on official Russian lists.

Thus, we note that in the official lists there are 19 pairs exploded on the same day. Two of them were on the same day but are known to be separated by a long time interval: # 414 and # 415 (December 16, 1974, Degelen) with more then three hours time interval; and # 440 and # 441 (April 21, 1976, at Degelen and Balapan and hence with a significant spatial separation) with a four minutes interval.

For the remaining 17 pairs of UNTs, only for four pairs were both tests detected and reported in the standard western publications. These tests were conducted on Dec 10, 1972 (# 376 and # 377, time interval 10 sec), on Oct 29, 1977 (# 473 and # 474, time interval 4.9 sec), on Aug 29, 1978 (# 493 and # 494, time interval 8.8 sec) and Nov 29, 1978 (# 506 and # 507, time interval 4.8 sec). In all four cases, the two tests were carried out in different areas (Balapan or Degelen) at separations of 50 km and more, which significantly facilitated their identification as test pairs.

The last 13 pairs of UNTs are shown in Table 2. Among them are 12 pairs for which just one UNT (for each pair) was reported by ISC; and one pair (Dec 5, 1980, # 561 and # 562) for which neither test was reported. In the last column of Table 2 are the numbers of the 14 UNTs unreported by the ISC. Only for one pair of UNTs (1980 Dec 5) were both tests unreported by the ISC, so one event from this pair potentially can be detected. The remaining 13 UNTs could not be detected by standard methods.

Table 2. 13 pairs of UNTs at STS which were exploded simultaneously or with very short time interval.

N	Date	Subarea	Detected test #	mb	Undetected test #
1	1970 Jun 28	Both Degelen	321	5.7	322
2	1970 Sep 06	Both Degelen	325	5.4	326
3	1971 Mar 22	Both Degelen	333	5.7	334
4	1971 Dec 30	Both Degelen	354	5.7	353
5	1972 Jun 07	Both Degelen	360	5.4	361
6	1975 Feb 20	Both Degelen	417	5.7	418
7	1976 Dec 07	Both Balapan	454	5.9	455
8	1977 Mar 29	Degelen	457	5.4	-
		Murzhik	-	-	458
9	1977 Dec 26	Both Degelen	479	4.9	480
10	1979 Jul 18	Murzhik	524	5.2	-
		Degelen	-	-	525
11	1980 Dec 05	Both Degelen	-	-	561 & 562
			Both tests were undetected.		
12	1983 Nov 29	Both Degelen	629	5.4	630
13	1987 Apr 03	Balapan	671	6.1	-
		Degelen	-	-	672

2.2.2.3 <u>Small UNTs with yield more than 1 ton, not reported by the ISC.</u> These events, listed in Table 3, are most interesting for us because potentially they can be detected at regional distances. They are the main object of our investigation.

We note that a total of 61 previously undocumented UNTs are given in Tables 1, 2, and 3, namely, 15 UNTs with yield less than 1 ton; 13 UNTs that occurred at essentially the same time as another UNT, including one of the pair # 561 and # 562; and 33 UNTs which potentially can be detected at regional distances, including the other of the pair # 561 and # 562. In section 3 below, we report our locations and magnitudes, based on regional detections, for most of these 33 UNTs.

Table 3. List of 33 separate UNTs (Y > 1 ton) which were not reported in standard western publications, but which potentially can be detected at regional distances.

N	Date	Sub area	N	Date	Sub area
1	1964 Jun 06	Deg	18	1974 Jul 29	Bal
2	1964 Aug 18	Deg	19	1974 Nov 28	Mur
3	1964 Sep 30	Deg	20	1975 Jul 15	Deg
4	1965 Feb 04	Deg	21	1975 Oct 05	Deg
5	1965 Mar 27	Deg	22	1976 Mar 17	Deg
6	1966 Oct 29	Deg	23	1976 Apr 10	Deg
7	1966 Nov 19	Deg	24	1976 Aug 04	Mur
8	1967 Sep 02	Deg	25	1977 Nov 12	Bal
9	1968 Oct 29	Deg	26	1977 Nov 27	Deg
10	1969 Apr 04	Deg	27	1980 Jun 25	Deg
11	1969 Apr 13	Deg	28	1980 Oct 23	Deg
12	1969 Oct 30	Deg	29	1980 Dec 05	Deg
13	1969 Nov 27	Deg	30	1983 Nov 02	Deg
14	1971 Jan 29	Deg	31	1985 Jul 11	Deg
15	1971 Apr 09	Deg	32	1985 Jul 19	Deg
16	1973 Nov 04	Bal	33	1988 Dec 28	Deg
17	1973 Dec 31	Deg			

2.3 Regional Data and Methods of Analysis for Small-Magnitude Seismic Events from STS.

Our work on this subject was carried out in two stages. The first, in late 1993, resulted in a technical report (Khalturin et al., 1994), produced prior to the publication of the first Russian preliminary list of Soviet UNTs (Gorin et al., 1994). Information about the dates on which UNTs occurred, and ground truth locations, were not then available for us. We used regional data, and tried to detect and locate all seismic events at STS which could be UNTs, chemical explosions or earthquakes. The second stage was carried out in 1997 – 99, in light of official information on UNT dates and acquisition of ground truth locations. Naturally, the magnitude threshold of detected signals in the first stage was significantly higher then in the second stage.

2.3.1 System of observations, stations and instrumentation.

Our results are based mainly on seismic data acquired by the Complex Seismological Expedition (CSE) of the Institute of the Physics of the Earth, Russian Academy of Sciences. Also we used bulletins of other regional stations of Central Asia including the Altai region. In total we used the records or bulletins of more than 50 seismographic stations. Most of them were operated on a temporary basis, and typically we used data from about 3 to 6 stations for each event to estimate its location. Most useful for detecting and locating small magnitude UNTs, were seismograms of narrow-band short period instruments installed in several stations by CSE in North Kazakhstan at distances of 500 km to 1200 km from STS. Long-term CSE observations in this region show that high-frequency regional phases propagate very efficiently. Also very helpful for detection and discrimination were records of "multichannel frequency selected stations", known from their Russian acronym as "ChISS", installed at the base stations Zerenda, Talgar, Novosibirsk (all in the distance range 740 – 780 km from STS) and Garm (1350 km from STS). These stations included the ChISS set of 8 or 12 channels from 0.5 to 45 hz or from 0.025 to 45 hz. Base stations also operated instruments as characterized in Table 4 and Figure 2.

Table 4. Main parameters of instrumentation installed at base stations and temporary stations of CSE.

Type	Abr.	T1-T2, sec	Magnification
Broad-band, long period	SKD	0.2 - 18	1,000 to 1,500
Broad-band, short period	SKM	0.07 - 1.4	30,000 to 60,000
Narrow-band	RVZT	0.2 - 1.2	100,000 to 300,000
Narrow-band, high gain	CSE	0.7 - 1.1	500,000 to 1,100,000

Two different types of high-gain short-period instruments — RVZT and CSE (see Table 4 and Figure 2) — were developed for detection of low-magnitude UNEs. Several places were found (the best ones were on the Kokchetav massif in Northern Kazakhstan) where magnification could be set as high as one million, with noise amplitudes only about 1 mm on the paper record, even though the attenuation of regional waves was very low. Figure 3 gives an example of such a high gain record, for an event not previously documented by standard western publications. It is the UNT of January 29, 1971. This signal was recorded by a CSE instrument located near the site of the present-day Zerenda broadband station (ZRN) on the Kokchetav massif, at a distance of 720 km with S/N ratio about 150 – 200.

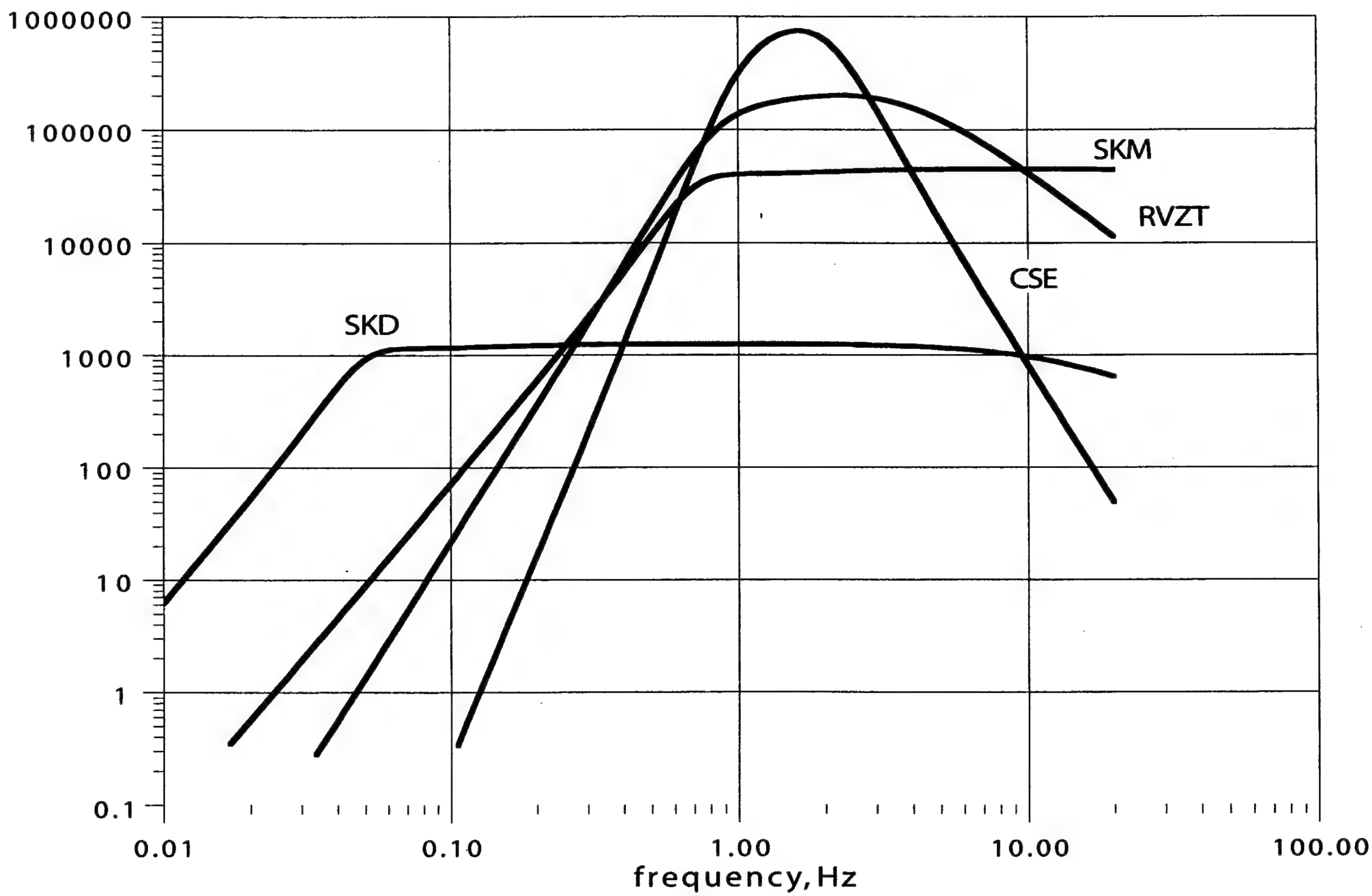


Figure 2. Responses of standard seismographic instruments used by the Complex Seismological Expedition for regional recording of UNTs at STS.

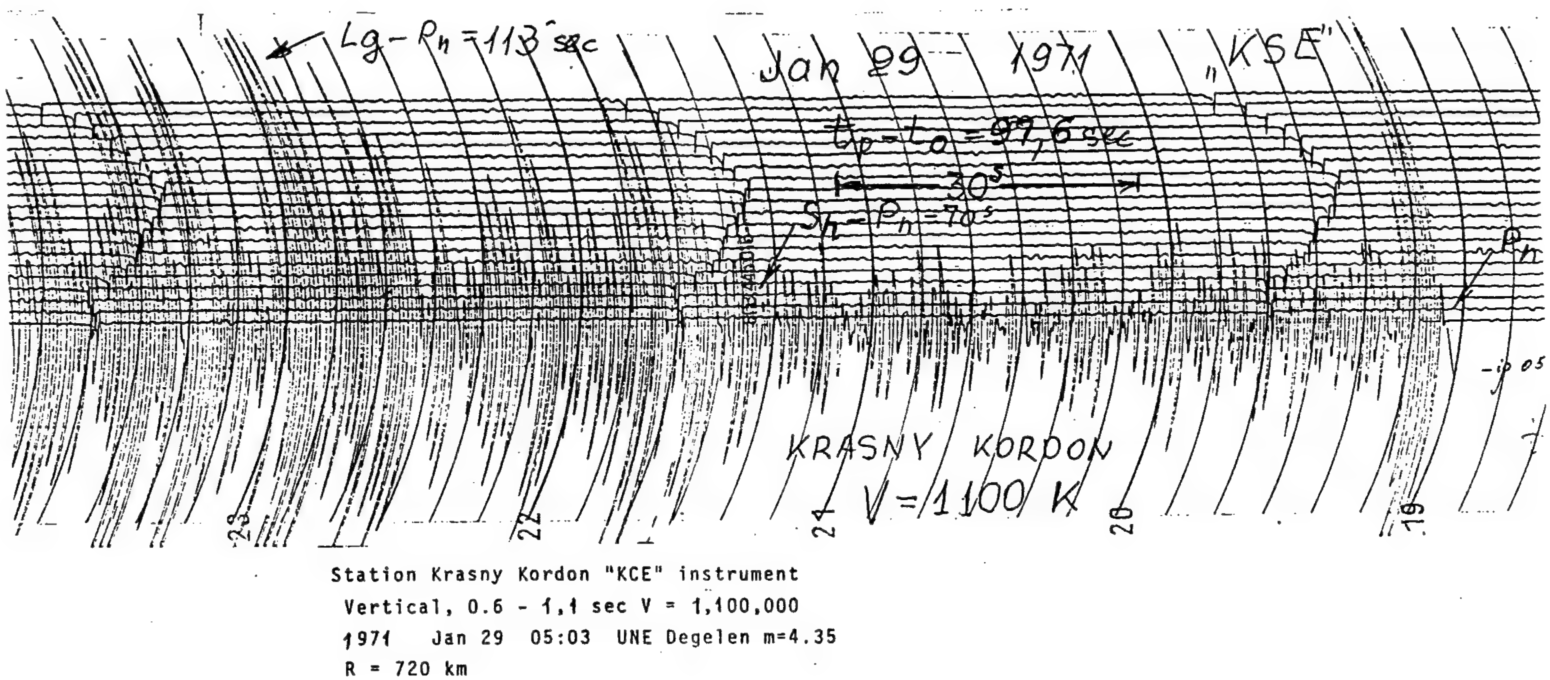


Figure 3. Example of a low noise short-period record with a gain of 1.1 million at Krasny Kordon, of a previously undocumented UNT at Degelen on Jan 19, 1971; *mb* 4.47 at a distance of 720 km. Time runs from right to left in these and other analog records from the Soviet Union.

ChISS instruments were installed in Talgar and Garm in September 1961, prior to the first UNT conducted at STS. Later, ChISS instruments were installed by the Complex Seismological Expedition (CSE) in Zerenda and Novosibirsk. They operated until the end of 1990. Figure 4 gives a ChISS record of the first Soviet underground nuclear explosion, at STS on October 11, 1961. These historic data are of remarkably high quality. ChISS records such as these are very effective even today for quantifying frequency-dependent features of regional seismic wave propagation. After 1969, ChISS instruments with ink-pen recording were installed by CSE for military seismic surveys in several places including Semipalatinsk, Makanchi (East Kazakhstan), Mongolia, Mayli-Say (East Fergana), and Malin (Northern Ukraine). The main goal was detection and prompt discrimination of the signals from underground and atmospheric nuclear explosions from non-Soviet test sites (Chinese nuclear testing in the atmosphere continued up to 1980). Discrimination was based on measurement of *P*-wave amplitudes on high frequency channels, and *S*, *Lg*, and *Rg* on low frequency channels. Figure 5 shows regional phases on the ChISS record at Talgar of a Degelen UNT, $mb = 5.08$. On the different narrowband channels the calibration signal can be clearly seen, with frequency changing slowly from 40 – 45 hz down to 0.3 – 0.5 hz and thus appearing on different channels at different times.

2.3.2 Regional phases observed from UNEs at STS.

The following regional phases are observed from the Semipalatinsk underground nuclear tests at distances up to 1200 km:

- *Pg* (6.15 km/s), *Sg* (3.55 km/s) and *Rg* (2.6 – 2.8 km/s) observed up to 230 – 250 km;
- *Pn*, appearing beyond 230 – 250 km as the first arrival with velocity 8.1 km/s. Its velocity stays constant up to distances of 800 – 900 km and then starts to increase slightly. Following *Pn* out to 800 – 900 km, *Pg* is observed with velocity 6.2 km/s.
- *Sn* is also observed (4.7 km/s) beyond about 240 km, but it is weak and can be clearly detected only on 60-70% of the records.
- A very intensive *Lg* group is observed beyond about 240 km with an impulsive onset. Usually the amplitude of *Lg* is 4 to 8 times bigger than amplitudes of *Pn* or *Pg*. Beyond 400 – 500 km the *Lg* wave train consists of two groups, denoted as Lg_1 and Lg_2, with velocities 3.55 and 3.40 km/s.
- An intensive *Rg* wave train is observed for UNEs with magnitudes greater than 5 on the long-period records. The train is short and consists of 1.5 to 2 cycles without clear dispersion. The velocity of the apparent first arrival is 3.0 km/s for periods 7 – 10 s.

Figure 5, showing five ChISS channels recorded at distance 730 km for a Degelen UNT of magnitude 5.08, indicates that the phases *Pg*, *Pn* (marked as P_1), *Sn*, Lg_1 and Lg_2 can be clearly seen, often with impulsive arrivals.

Khalturin et al. (1994) describe how these regional travel time – distance relations were used to estimate the location and location accuracy of small seismic events at STS.

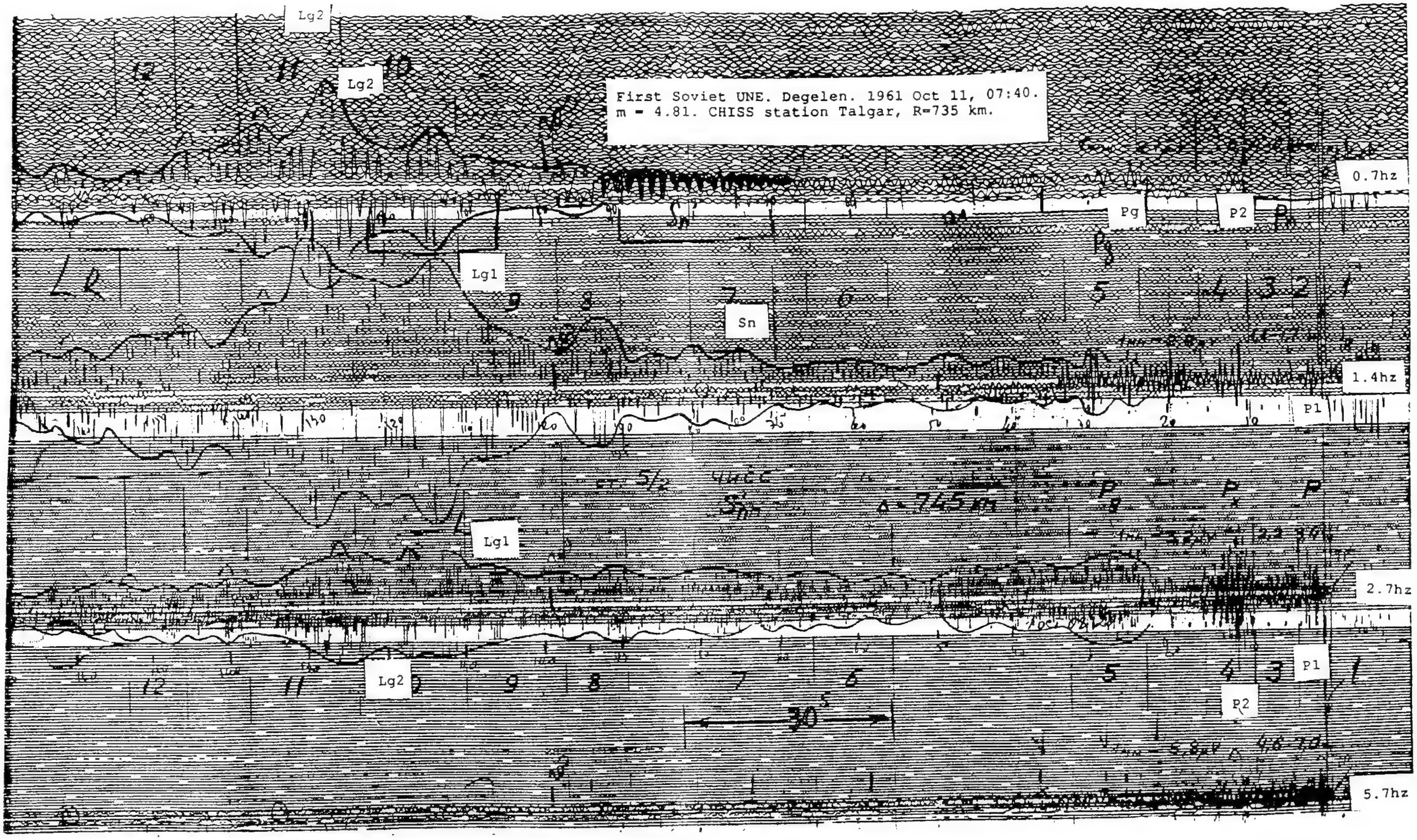


Figure 4. The ChISS record at Talgar of the first underground nuclear explosion at the Semipalatinsk Test Site, on October 11, 1961. Distance is 735 km. The phase marked here as *P1* is the *Pn* wave, and is strong at high frequencies. It even appears clearly on the 11 hz channel (not shown here). The phase marked as *P2*, between *P1* and *Pg*, is strong at Talgar for Degelen explosions. *P2* is three times smaller at Talgar for Balapan explosions. *Lg* waves are strong, particularly on the 1.4 hz and 0.7 hz channels, with amplitude about 6 to 10 times that of the *P*-wave — a typical ratio for UNE records at many stations around STS at distances 500 – 1300 km. *Lg* is weak on channels (not shown here) of frequency lower than 0.7 hz, in contrast to the strong low-frequency *Lg* of typical earthquakes. The magnitude value 4.78 is supported by several stations. Using the *mb* – yield relation of Ringdal et al. (1992), this magnitude corresponds to a yield of 2.7 kilotons — somewhat higher than the announced yield of 1 kiloton for this event.

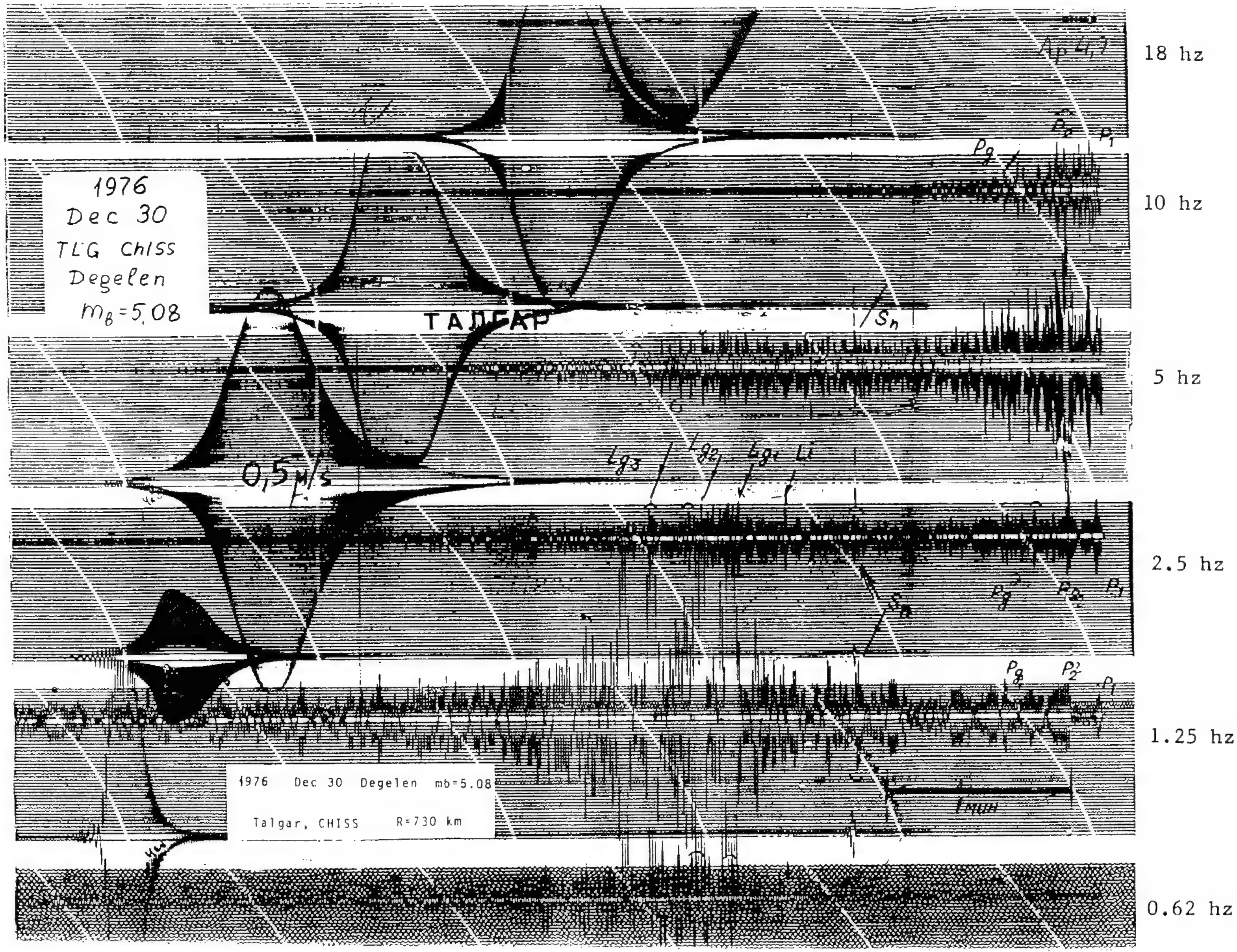


Figure 5. The ChISS record at Talgar, of the Degelen UNE of December 30, 1976, with *mb* 5.08. Note the strong *Pn* arrival (marked as *P1*) on 10 hz and 5 hz channels, whereas *Lg* is strongest on the 1.25 hz channel. A calibration signal is given for all these narrowband channels, corresponding to a sinusoidal ground velocity (with slowly varying period) whose amplitude has the constant value of 0.5 micron/s.

2.3.3 Magnitude determination.

Two methods were used to assign magnitudes (*mb*) from regional data. The first method was based on the *K* scale (energy class), which is still used in the former Soviet Union by analysts at all local networks, for characterizing the size of seismic events using data acquired at distances up to 3000 km. The energy class *K* is calculated from the sum of max *P* amplitude, and max *S* or *Lg* amplitude, on records of the short-period instrument SKM. For UNEs and chemical explosions at STS, Khalturin et al. (1998) report the following relationship between *K* values, and *mb* values as given by the British Atomic Weapons Establishment and by NORSAR:

$$mb(K) = 0.46\,K - 0.64. \quad (1)$$

We used this relationship in the present study, to assign *mb* values when the *K* value was available.

The second method to assign *mb* was based on calibration of a measurement of the maximum amplitude of *Lg* waves. This scale was typically applied to the narrow-band records. The resulting magnitude is denoted as *mb(Lg)*.

2.4 Detection of Small Events from STS from Regional Recordings in Kazakhstan and Central Asia.

2.4.1 Monitoring of seismic signals from STS: detection and identification.

The seismographic network operated by CSE was used to acquire observations in the Kazakhstan region throughout the period of UNT activity at STS — from 1961 to 1989. During the long-term monitoring effort, besides the well-known intermediate and large magnitude UNTs from STS, several tens of small magnitude events were detected that were not mentioned by Lilwall and Farthing (1990), or Ringdal et al. (1992). These events can be UNTs, or they could be chemical explosions used for military experiments and for construction. Few of these signals can be from earthquakes, which are very rare in the Semipalatinsk region since it is located on the far western flank of the Altai seismic zone.

Our first stage of study (Khalturin et al., 1994) examined data for 57 of these events that were on or near STS; estimated their coordinates, origin time, and magnitude; and made a preliminary identification as to the nature of each event (nuclear or chemical explosion, or earthquake). We now know that these 57 events consisted of 19 UNTs, 27 chemical explosions, 8 small magnitude UNTs known from Bocharov et al. (1989), and three earthquakes. Our first stage identified all of the UNTs and earthquakes correctly, but wrongly listed two of the chemical explosions as UNTs, and two other chemical explosions as "either UNE or chemical explosion".

Our second stage of study, in this paper, done following the release of UNT date information, has examined data for 71 events on or near STS, and has resulted in estimates of the origin time and magnitude of an additional 12 small UNTs which were missed in the first stage. So, from the 33 previously undocumented UNTs of Table 3, our first stage of study uncovered 19 UNTs and the present paper documents another 12. The present paper also includes two more

chemical explosions than our first study: that of September 15, 1984 (previously listed by some papers as a UNT), and the chemical explosion carried out in 1987 as part of a Joint US-Soviet Experiment of the USSR Academy of Sciences and the US Natural Resources Defense Council (see Given et al., 1990).

2.4.1.1 Earthquakes near the Semipalatinsk Test Site. Among the 71 regionally-recorded events were three earthquakes, given in Table 5, which occurred near the border of STS or in the surrounding area. This Table also lists three more recent earthquakes in the region.

In Table 5, event #1 was described by Khalturin et al. (1994). Event #2 was widely detected, and it is still sometimes listed as a UNT though the seismological basis for identifying it as an earthquake was given several years ago (Pooley et al., 1983). Event #3 was reported by the ISC (47.9N 83.5E, *mb* 4.5) and listed by Sykes and Ruggi (1989) as a Soviet UNE at (50N, 79E) with *mb* 3.6. Events ##4 – 6 occurred near STS after the period of our study. Event #5 was reported in the US Geological Survey's Preliminary Determination of Epicenters. Events #4 and 6 have been reported by the Altay-Sayan Seismological Expedition, based in Novosibirsk.

Table 5. Earthquakes located near the Semipalatinsk Test Site during 1961 – 1989 (##1-3) and examples of more recent earthquakes (##4-6).

#	Date	Time	Lat.	Long.	K	mb(K)
1.	1966 Dec 26	17:39:38.5	49.52	78.71	10.7	4.28
2.	1976 Mar 20	04:03:36	50.00	77.25	12.9	5.34
3.	1981 Mar 31	07:51:30	47.80	81.00	12.2	4.96
4.	1995 Mar 6	05:27:13	48.4	78.1	9.2	3.6
5.	1996 Mar 26	13:58:12	50.085	77.097	11.3	4.2
6.	1996 Sep 25	19:24:01	47.7	80.2	10.9	4.0

2.4.1.2 Chemical explosions at the Semipalatinsk Test Site.

The remaining 60 regionally-recorded events have all the characteristics of explosions. Comparing their origin times with the list of UNT dates contained in Russian official publications issued in 1996 – 1997 we now conclude that 29 were chemical explosions at STS, and 31 were indeed UNTs at STS. Parameters of the 29 chemical explosions are given in Table 6. More than half of these chemical explosions were assumed in some publications during the late 1980s to be UNTs from STS. It is of course appropriate to list all candidate UNEs in projects that set out to evaluate monitoring capability.

In Table 6, origin time, coordinates and *K* values were obtained from CSE observations; the magnitude value *m*(NOR) refers to magnitudes obtained from F. Ringdal [personal communication, 1994]; magnitudes in parentheses ( ) were assigned by Hagfors (HFS) and are known typically to be significantly higher than *m*(NOR) values; and *mb*(*K*) is the body wave magnitude calculated from energy class *K* using the relationship $mb(K) = 0.46\,K - 0.64$.

Table 6. 29 chemical explosions at the Semipalatinsk Test Site during 1961 – 1989 which were detected and located from CSE observations.

Date	Time	Lat	Long	K	m(NOR)	mb(K)	Notes
1961 Jun 05	03:50:00	49.77	77.98	11.0	-	4.42	A
1973 Mar 23	06:30:00	49.94	79.06	9.53	3.7	3.74	
1974 Sep 27	07:34:00	49.98	79.00	10.47	4.0	4.16	
1978 Jul 31	08:00:00	50.42	77.87	10.2	3.9	4.05	B
1979 May 24	04:07:00	49.94	78.79	10.33	3.9	4.05	SR-1
1979 Sep 14	07:33:00	49.95	78.84	10.75	4.4	4.30	SR-2
1979 Sep 15	04:07:00	49.94	78.82	8.85	3.8	3.44	
1980 Jul 13	08:10:00	49.91	78.84	10.33	(5.0)	4.10	SR-3
1980 Sep 20	10:40:01	49.96	78.88	9.83	3.8	3.88	SR-4
1980 Sep 30	05:57:12	49.95	78.40	-	3.6	-	SR-5
1980 Sep 30	05:57:17	49.95	78.40	11.03	4.4	4.42	SR-6
1980 Nov 06	17:42:58	50.14	78.76	9.17	3.9	3.56	
1981 May 28	04:08:28	50.00	78.00	7.70	-	2.90	
1981 Jun 05	03:22:18	49.84	78.72	10.30	4.0	4.10	SR-7
1981 Jul 05	03:59:14	49.87	78.99	10.47	(4.6)	4.17	SR-8
1981 Sep 30	12:55:10	49.94	78.90	10.70	4.3	4.28	SR-9
1981 Nov 19	05:57:14	50.11	78.95	9.60	4.0	3.78	
1982 Jun 11	10:59:07	49.90	77.90	10.65	4.1	4.26	SR-10
1982 Jul 12	10:29:18	49.90	77.90	10.67	3.9	4.27	SR-11
1982 Sep 04	05:47:17	50.06	78.56	9.47	3.6	3.72	SR-12
1982 Sep 15	04:33:19	49.85	78.85	10.86	4.2	4.36	SR-13
1983 Jul 28	03:41:28	50.07	78.60	10.74	4.3	4.34	SR-14
1984 Jun 23	02:57:16	49.92	78.93	11.06	4.4	4.44	SR-15
1984 Sep 15	06:15:10	49.99	78.88	11.17	-	4.48	C and SR-16
1985 Jun 27	11:57:04	49.78	77.97	8.5	-	3.27	D
1987 Jun 29	04:55:08	49.78	77.97	8.5	-	3.27	D
1987 Sep 02	09:27:05	50.00	70.34	-	2.7	-	E
1987 Sep 16	07:30:01	49.86	78.73	10.64	4.3	4.26	SR-17
1988 Sep 26	07:45:04	50.08	78.80	10.41	4.3	4.15	F

Notes on Table 6:
A — Fully contained explosion with a yield of 600 tons of TNT, carried out in a Degelen Mountain tunnel prior to the start of nuclear testing (Sultanov et al. 1995). Goals included calibration of a seismic network and estimation of the expected seismic signal strength at different distances.
B — Large experimental chemical explosion on the surface with a yield of 5000 tons.
C — This chemical explosion has been wrongly listed as an underground nuclear test, in some cases with mb = 5.04; for example see Lilwall and Farthing (1990), and Ringdal, Marshall, and Alewine (1992). For this chemical explosion, mb(ISC) = 4.7, mb(HFS) = 5.2.
D — These two experimental chemical explosions, each of 500 tons of TNT, were conducted by the Institute of Dynamics of the Geospheres (IDG) at the same place on the surface of Degelen Mountain near the mouth of tunnel #160 (49.7841°N, 77.96722°E). See Adushkin et al. (1997).
E — Chemical explosion (yield 20 tons, depth 25 m) carried out in the Degelen sub-area during the Joint US-Soviet Experiment of the USSR Academy of Sciences and the US Natural Resources Defense Council (see Given et al., 1990).
F — Hansen et al. (1990) assumed this chemical explosion was an underground nuclear test in their study of the stability of RMS Lg.
SR — Sykes and Ruggi (1986, 1989) list all these 15 chemical explosions as UNTs from STS with the following mb values:

1 - 4.9;	2 - 5.2	3 - 5.0;	4 - 4.9;	5 - 4.6;	6 - 5.2;
7 - 4.7;	8 - 4.6;	9 - 4.6;	10 - 4.6;	11 - 4.6;	12 - 4.1;
13 - 5.0;	14 - 5.0;	15 - 4.4;	16 - 5.2;	17 - 5.0.	

Some if not all of these magnitudes are from the Hagfors Observatory (HFS). On average HFS magnitudes are larger than NORSAR magnitudes by about 0.6 – 0.8 magnitude units.
A very weak regional signal originating on October 20, 1989 at 13:22:45 from about (50°N, 78°E) may be a chemical explosion or a collapse of the cavity from a previous UNE.

More recently than the period of our study, chemical explosions ranging in size from a few kilograms up to 100 tons have been carried out in Kazakhstan in a cooperative program between the National Nuclear Centre of the Republic of Kazakhstan and the US Defense Threat Reduction Agency. Times and locations of such explosions larger than one ton are listed in Table 7. Both calibration explosions listed with $Y = 100$ tons were carried out at Degelen in tunnels. Their *mb* values (3.7 - 3.8) correspond to the upper limit of $mb(Y)$ relationship described in Khalturin at al. (1998). All other explosions were made at Balapan in shafts.

2.4.2 Detection and analysis of small UNTs from STS.

Here we give the origin times, locations and magnitudes of small UNTs whose detection and or location was not previously well-documented by western seismologists in the open literature. We also give magnitude values based on regional detections, for 8 small events whose hypocenter coordinates have been available from Bocharov et al. (1989).

Table 7. Calibration chemical explosions at the Semipalatinsk Test Site since 1997.

Date	Time	Lat.	Long.	Depth, m	Y, tons
1997 Jul 13	08.11.08.799	49.8786	78.7601	630	5.00
1997 Aug 03	08:07:20.04	49.9781	78.8200	50	25
1997 Aug 31	07:08:39.26	49.8837	78.8148	360	25
1997 Sep 28	07:30:15.13	49.8802	78.7587	550	25
1998 Jul 13	10.44.56.363	49.8801	78.6921	20	2.03
1998 Jul 14	05.11.35.570	49.9315	78.7871	20	2.03
1998 Jul 14	08.19.39.296	49.9129	78.7488	20	2.03
1998 Aug 14	04.26.52.813	50.0357	79.0114	13	2.03
1998 Aug 14	05.39.24.970	50.0576	78.9387	2.5	2.03
1998 Aug 15	02.40.59.116	49.8724	78.6478	14	2.03
1998 Aug 15	05.05.11.156	49.8786	78.7601	630	2.03
1998 Aug 22	05:00:18.90	49.7667	77.9908		100 (mb=3.8)
1998 Sep 17	07:19:40.44	49.9810	78.7559	30	25
1999 Sep 25	05:00:05.7	49.7841	77.8240		100 (mb=3.7)

2.4.2.1 <u>Main parameters of previously undocumented small UNTs.</u> For the 33 small UNTs listed in Table 3, we have found regional seismic detections at temporary and permanent stations of the CSE for all but two events. Parameters for the 33 events are listed in Table 8. Origin times were estimated for 31 of them. For the 19 largest of these small events, we obtained location estimates based on seismic signals, and K values and hence mb(K). For the 12 smallest events we give estimated mb(Lg) values — which range from 2.2 to 3.7.

During the course of our work, ground truth information on locations became available from Leith (1998) and NNCRK (1999) for 30 of the UNTs, and in section 4 we discuss the accuracy of our seismically-estimated locations. Thus, origin time, *K* and *mb*(*Lg*) of all UNTs, and coordinates of the 1976 Aug 4 UNE, are our estimates based on regional observations of the CSE. Coordinates of all other UNTs are ground truth values.

Table 8. Parameters of small announced UNTs studied in this paper.

Date	Time	Subarea	Lat	Long	K	mb(K)	mb(Lg) or m(NOR)	Note
1964 Jun 06	00:00:00	Deg	49.7747	77.9881	11.0	4.42	-	
1964 Aug 18	06:00:00	Deg	49.8206	78.0819	8.5	3.27	-	
1964 Sep 30	Not detected							
1965 Feb 04	06:00:00	Deg	49.7731	77.9914	12.5	5.10	-	A
1965 Mar 27	06:30:00	Deg	49.7747	77.9881	8.4	3.22	-	
1966 Oct 29	03:58:00	Deg	49.7847	77.9994	9.0	3.50	-	
1966 Nov 19	03:58:00	Deg	49.8297	78.0575	8.7	3.36	-	
1967 Sep 02	04:04:00	Deg	49.7419	78.0256	10.3	4.10	-	
1968 Oct 29	03:54:00	Deg	49.8333	78.0928	10.8	4.33	-	
1969 Apr 04	04:57:00	Deg	49.7533	78.0536	9.2	3.60	-	
1969 Apr 13	04:04:00	Deg	49.7356	78.1047	1.3	4.55	-	
1969 Oct 30	Not detected							
1969 Nov 27	05:02:00	Deg	49.8367	78.0597	10.3	4.10	-	
1971 Jan 29	05:03:00	Deg	49.8053	78.1686	11.1	4.47	-	
1971 Apr 09	02:33:00	Deg	49.8322	78.0386	9.6	3.78	-	B
1973 Nov 04	03:57:00	Bal	50.0716	78.9362	-	-	2.6-Lg	
1973 Dec 31	04:03:00	Deg	49.7394	78.0863	10.6	4.24	4.0-Nor	
1974 Jul 29	03:28:00	Bal	49.9375	78.9358	-	-	3.3-Lg	
1974 Nov 28	05:57:00	Mur	n/a		-	-	2.8-Lg	
1975 Jul 15	02:57:00	Deg	49.7914	78.0944	-	-	3.3-Lg	
1975 Oct 05	04:27:00	Deg	49.7831	78.0867	10.7	4.28	4.0-Nor	SR-1
1976 Mar 17	02:57:00	Deg	49.7556	78.0992	-	-	2.2-Lg	
1976 Apr 10	05:03:00	Deg	49.7550	78.0475	-	-	3.0-Lg	
1976 Aug 04	02:57:00	Mur	49.87	77.7	10.5	4.20	3.8-Nor	SR-2
1977 Nov 12	05:11:00	Bal	50.0522	78.8644	-	-	2.8-Lg	
1977 Nov 27	03:57:00	Deg	49.7544	78.0503	9.9	3.92	3.4-Nor	
1980 Jun 25	02:27:00	Deg	49.8258	78.0994	-	--	3.7-Lg	
1980 Oct 23	03:57:11	Deg	49.7517	78.1317	-	-	2.5-Lg	
1980 Dec 05	04:17:16	Deg	49.7517	78.1317	-	-	3.6-Lg	
1983 Nov 02	04:18:54	Deg	49.7792	78.1247	-	-	3.0-Lg	
1985 Jul 11	02:57:02	Deg	49.7506	78.0492	10.2	4.05	3.5-Nor	SR-3
1985 Jul 19	04:00:08	Deg	49.8011	78.0686	-	-	2.5-Lg	
1988 Dec 28	05:28:10	Deg	49.8011	78.0686	9.5	3.74	3.6-Nor	C

Notes on Table 8:
mb(K) — calculation of mb from K using the relationship: mb(K) = 0.46 K – 0.64.
m(NOR) — from F. Ringdal (pers. comm., 1994), based on teleseismic signals at NORSAR.

A — This event was obscured by many Aleutian earthquakes, up to mb 6.4 on that day.
B — The yield of this explosion has been announced as 0.23 kt (USSR Nuclear Tests, 1997)
C — This event was mentioned by Ringdal (1990).
SR — These three events are listed by Sykes and Ruggi (1986, 1989) with the following coordinates and magnitudes mb:

1. 55.8N and 75.1E; mb = 4.6.
2. 49.9N and 77.7E; mb = 4.1.
3. 50.0N and 78.0E; mb = 4.0.

One relatively large UNT, with *mb(K)* 5.1 (February 4, 1965), was not reported by standard western publications as it was obscured teleseismically by a swarm of Aleutian earthquakes. We believe this was a coincidence rather than an effort to obscure the event, because the origin time (06:00:00) was typical for UNTs of the mid-1960s. But even if we exclude this large event, the *mb* value (calculated from *K*) for missed events ranges up to 4.55, and during 1964 – 1989, about 10 Soviet UNTs at STS, with magnitude 4.0 or more, had teleseismic signals that were too weak or too noisy to lead to publication of good location estimates. Some of these events were detected teleseismically at particular arrays (Ringdal, 1990).

2.4.2.2 Magnitude estimation of small known UNTs. Among the analysed signals were 8 small UNEs known from Bocharov et al. (1989) but listed there without magnitudes. Four of these events had been reported using teleseismic signals by Sykes and Ruggi (1986, 1989), who also listed a magnitude for three of the events.

For these 8 events the energy class *K* is known from regional records at several stations, allowing us to give values of *mb(K)* which we list in Table 9. The other *mb* values are from Sykes ad Ruggi (1989).

2.5 Comparison of Ground Truth and Seismologically-Determined Locations of Small Magnitude UNTs from STS.

Our earlier study (Khalturin et al. 1994) determined coordinates of 18 small-magnitude UNTs (one additional UNT was detected only by one station) on the basis of arrival times of regional waves, and estimated the location uncertainty, which was typically an area of the order of 100 km^2. One of those UNTs was at Murzhik for which we do not yet know the ground truth coordinates. Thus for 17 UNTs (magnitudes 3.8-4.6), which occurred at Degelen, we can now compare the seismically-located epicenters with ground truth recently obtained for that sub-area by Leith (1998).

Table 9. 8 known UNTs for which we can now assign magnitudes.

Date	Time (to nearest s)	K	mb(K)	mb	Note
1961 Oct 11	07:40:00	11.8	4.78	-	A
1962 Feb 02	08:00:00	13.6	5.63	-	B-1
1965 Jul 29	06:00:00	10.7	4.28	4.5	B-2
1965 Oct 14	04:00:00	10.7	4.28	-	C
1968 Oct 21	03:52:00	10.2	4.05	-	C
1968 Nov 12	07:30:00	10.6	4.24	-	C
1970 May 27	04:03:00	10.3	4.20	3.8	B-3
1972 Dec 28	04:27:00	11.4	4.60	4.9	B-4

Notes on Table 9:
A – the first underground nuclear explosion conducted by the USSR was not included in many western lists of USSR explosions prior to publication of Bocharov et al. (1989), but it was reported (without coordinates and magnitude) by Bolt (1976), and by Sykes and Ruggi (1986, 1989).
B – detection and approximate location reported by Sykes and Ruggi (1986, 1989):
1 – no magnitude estimation;
2 – wrong time (03:05:00);
3 – coordinates with 150 km error;
4 – coordinates with 200 km error.
C – These UNTs were not published in western lists of USSR explosions prior to publication of Bocharov et al. (1989).

For these small UNTs, regional signals were acquired at CSE stations located at distances in the range 500–1400 km from STS. We mostly used data from bulletins but did read waveforms ourselves in some cases. Thus for these 17 UNTs we had 20 records and 49 station bulletin data from stations to the south; and 37 station bulletin data from stations to the east or west. So on average for the location of one event we had about one record and about three pieces of data from station bulletins located to the south of STS, and about 2 data from stations located to the east or west. On each record, 2 –3 regional phases were measured (typically *Pn*, *Sn*, *Lg*). To obtain a preliminary estimate of location and origin time, we usually used (if they were available) three values of time intervals such as $t(Lg) - t(Sn)$; $t(Lg) - (Pn)$ and $t(Sn) - t(Pn)$ from each station record or bulletin. Having estimated the origin time (t_0) in this way, the next step for location was to use time intervals such as $t(Pn) - t_0$; $t(Sn) - t_0$ and $t(Lg) - t_0$.

For event location we used travel times of regional phases as given by Nersesov and Rautian (1964), based on a Pamirs-Baikal profile, slightly adapted by Khalturin for Northeast Kazakhstan. Our locations, and the comparison with ground truth information, are given in Table 10. On average, the seismically-determined location error was only about 5 km. The ground truth location was found to lie within the interval specified by Khalturin et al. (1994) as the location uncertainty in almost all cases, and only marginally outside that interval in the few cases where it was outside. The average of absolute errors for all 17 UNTs is only 3.2 km in latitude, and 4.4 km in longitude. The average of signed errors is only 0.53 km in latitude and 0.45 km in longitude (i.e., real epicenters systematically lie 0.53 km south and 0.45 km west of our estimated locations). Since the average length of the seismic paths was 750 km, the systematic error is remarkable small — about 0.07%, corresponding to an error in velocity of about 0.005 km/s.

We have thus been able to demonstrate the utility of regional seismic waves for purposes of accurate estimation of UNT locations, even when only a few records are available per event. The location uncertainty is so small in our case, because of the availability of good information, appropriate to the region, on travel times. The strongest constraint typically came from values of the time interval between *Lg* and *Pn*.

2.6 Comment on Magnitude Distribution and Yields.

Now that we have obtained a fairly complete set of magnitudes for the nuclear tests at Semipalatinsk, it is of interest to see how they are distributed, and how well the announced information on yield is in accord with yield estimates based on seismic magnitude.

2.6.1 Comparison of seismically determined yields, and announced information on annual total yield.

USSR Nuclear Tests (1997) gave the total yield each year at each test site, and so we can compare these announced totals at STS for the years from 1964 to 1989 with the total obtained by summing the seismically determined yields. (The announced total yield at STS for the years 1961 and 1962 included several atmospheric tests; and in 1963 there were no tests. After 1963 all STS nuclear tests were underground.) Using the relation $mb = 4.45 + 0.75 \log Y$ advocated by Murphy (1990) and Ringdal et al. (1992), we have estimated the yield of all the STS tests for which we have a magnitude. Figure 6 compares the annual total of yields determined seismically with the officially announced yield information. The yield of tests for which we do not have a magnitude is insignificant in comparison with the well-documented tests. Note that the vertical axis for this histogram is linear in yield, rather than in logarithmic units. The agreement between seismically determined yield totals, and announced total is remarkable. The differences are somewhat greater than 10% in the earlier years, but are less than 10% for most of the last ten years of testing.

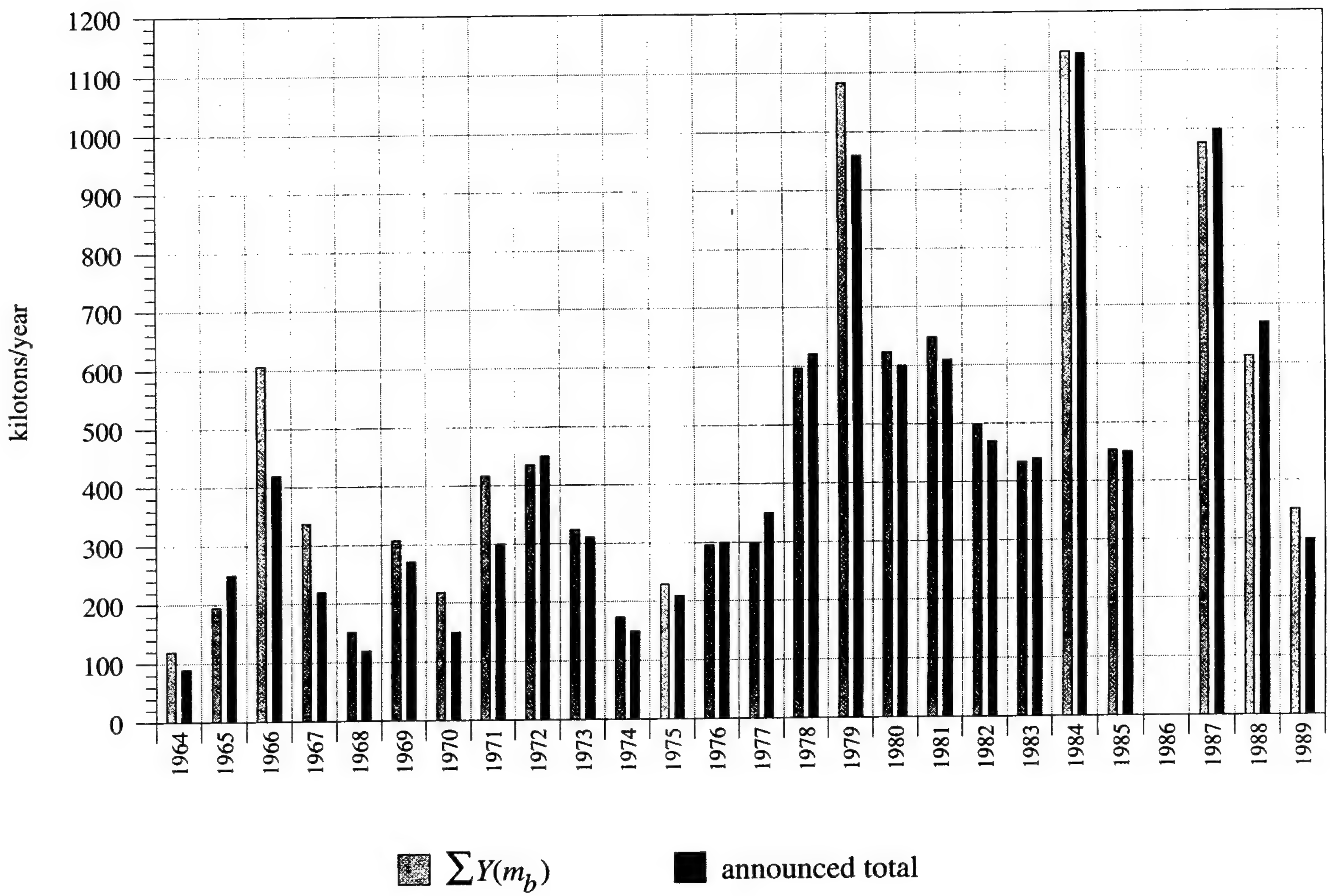


Figure 6. Estimated total yield per year at the Semipalatinsk Test Site (based on P-wave magnitudes).
The announced total yield each year, of underground nuclear tests at Semipalatinsk, is compared with the total obtained By summing the estimated yield using the relationship $Y = 10\text{^}((mb - 4.45)/0.75)$, based upon the *P*-wave magnitude (AWE), for previously well-documented events plus events characterized in this paper. The aggregate announced yield for the whole period 1964 – 1989 is 10.8 megatons (mt), whereas the aggregate seismically-estimated yield is 11.5 mt.

Table 10. Comparison of seismically-determined locations based on regional phases (Khalturin et al., 1994) and ground truth locations (Leith,1998), for small UNTs at the Semipalatinsk Test Site.

Date	Latitude Seism.	G.T.	ΔLat km	Longitude Seism.	G.T.	ΔLong km
1964 Jun 06	49.79	49.774	1.8	78.00	77.988	0.9
1964 Aug 18	49.81	49.821	-1.1	78.10	78.082	1.3
1965 Feb 04	49.78	49.773	0.8	78.12	77.991	9.2
1965 Mar 27	49.82	49.775	5.0	78.00	77.988	0.9
1966 Oct 29	49.74	49.785	-5.0	78.07	78.000	5.0
1966 Nov 19	49.70	49.730	-3.3	78.20	78.058	10.2
1967 Sep 02	49.79	49.742	5.3	78.02	78.026	-0.4
1968 Oct 29	49.84	49.833	0.8	78.14	78.093	3.3
1969 Apr 13	49.70	49.736	-4.0	77.92	78.105	-13.3
1969 Nov 27	49.79	49.837	-5.2	78.20	78.060	10.0
1971 Jan 29	49.77	49.805	-3.9	78.11	78.169	-4.2
1971 Apr 09	49.88	49.832	5.3	78.02	78.039	-1.4
1973 Dec 31	49.75	49.739	1.2	78.04	78.086	-3.3
1975 Oct 05	49.81	49.783	3.0	78.10	78.087	0.9
1977 Nov 27	49.80	49.754	5.1	78.06	78.050	0.7
1985 Jul 11	49.78	49.750	3.3	77.90	78.049	-10.7
1988 Dec 28	49.80	49.801	-0.1	78.06	78.069	-0.6

2.6.2 Detection threshold and magnitude distribution.

The small underground nuclear tests at STS provide some practical experience with certain aspects of open monitoring, albeit for years in the past, especially in the early years of underground nuclear testing, when capabilities were not as good as they are today. Thus, we can comment on three different levels of preliminary information about detected events: (a) monitoring in the teleseismic zone (distances greater than 3,000 km) without any information, other than the known position of the test site; (b) the same as case (a) but with stations located in the regional interval of epicentral distances (700 – 3,000 km); and (c) the same as case (b) but when the dates of UNTs (and preferably even narrower time intervals) are known.

As our example of case (a) we can take the 271 UNTs at STS reported as seismic events by the ISC during 1961 – 1989 (note, not all of these events were reported at the time as nuclear in origin). However, this is monitoring of events large enough to enable good estimates of location using seismological methods. As noted above, in discussing the magnitude of these ISC events we prefer to use *mb*(AWE) values rather than *mb*(ISC) since the latter are known to be routinely too large, particularly for events with *mb* less than about 5.0 (when the number of stations reporting magnitude is significantly lower, so that the ISC *mb* is biased by reliance on sensitive stations — see Ringdal, 1976). Case (b) corresponds to the first stage of our analysis of regional observations (Khalturin et al., 1994), using stations located in the 700 – 3000 km distance range, but with unknown origin times. Case (c) corresponds to the analysis presented in this paper, when dates of UNTs at STS were known.

It is reasonable to expect that the magnitude threshold for event reporting will decrease from case (a) to case (b) to case (c), and this expectation turns out to be correct. As a simple definition of the magnitude threshold, we chose the *mb* value at which 50% of the signals are unreported. For determination of magnitude threshold, we worked with magnitudes for three sets of UNTs:
(1) *mb*(AWE) for all UNTs from STS reported by the ISC;
(2) our determination of magnitudes of 27 small UNTs which were detected in the first stage of study, when days and times of explosions were not known;
(3) magnitudes of the 12 smallest UNEs which were detected later, when the date of each explosion was known. (In practice, it also proved helpful in searching for these data to know the times of day that were commonly used for UNTs at STS.)

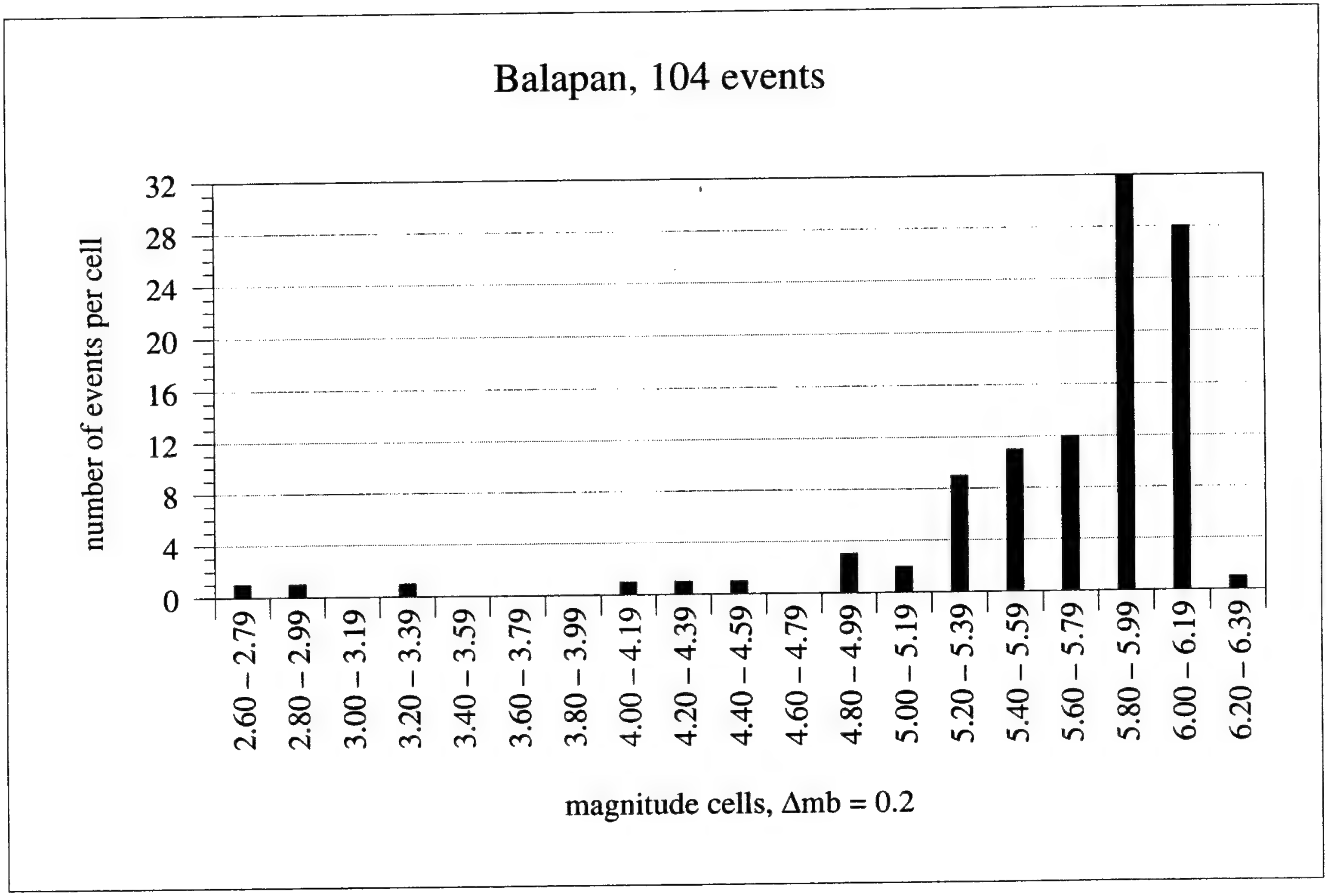
For each of the three sets of magnitudes, we made a histogram giving the number of events in cells of width 0.2 magnitude units. We found that in the magnitude interval 4.35 – 4.54, AWE assigned magnitudes for 8 events and 2 were missed by ISC; and in the magnitude interval 4.15 – 4.34, AWE assigned magnitudes for 4 events and 8 were missed by ISC. On this basis, the magnitude at which there was a 50% chance of an STS event being reported by the ISC corresponded to about *mb*(AWE) = 4.28. For CSE regional observations, case (b), inspection of the intervals 3.15 – 3.34 and 2.95 – 3.14 indicates the magnitude corresponding to 50% chance of detection was about *mb* 3.25.

The magnitude threshold for NORSAR in case (c), when the origin time is known, is very low for teleseismic signals from STS, *mb* 3.3 ± 0.1. Among the 29 chemical explosions recorded regionally by CSE, NORSAR reported about 23 events using teleseismic data. NORSAR also reported all six UNTs recorded by CSE but not reported by ISC since 1973 (when NORSAR started to operate). (The NORSAR Semi-annual report for April – September 1984 indicated a detection threshold for STS in the range *mb* 2.5 to 3.0.)

The study of Sykes and Ruggi (1989), published prior to the list of Bocharov et al. (1989), used numerous sources of information on teleseismic detections, including LASA and Hagfors detections of events that potentially could have been STS UNTs. An earlier and longer version of this paper is Sykes and Ruggi (1986), which gave references for the locations that were used, and stated that identification and size determination are much more questionable for events of equivalent yield less than 5 kt. Sykes and Ruggi's success was impressive in that they found six

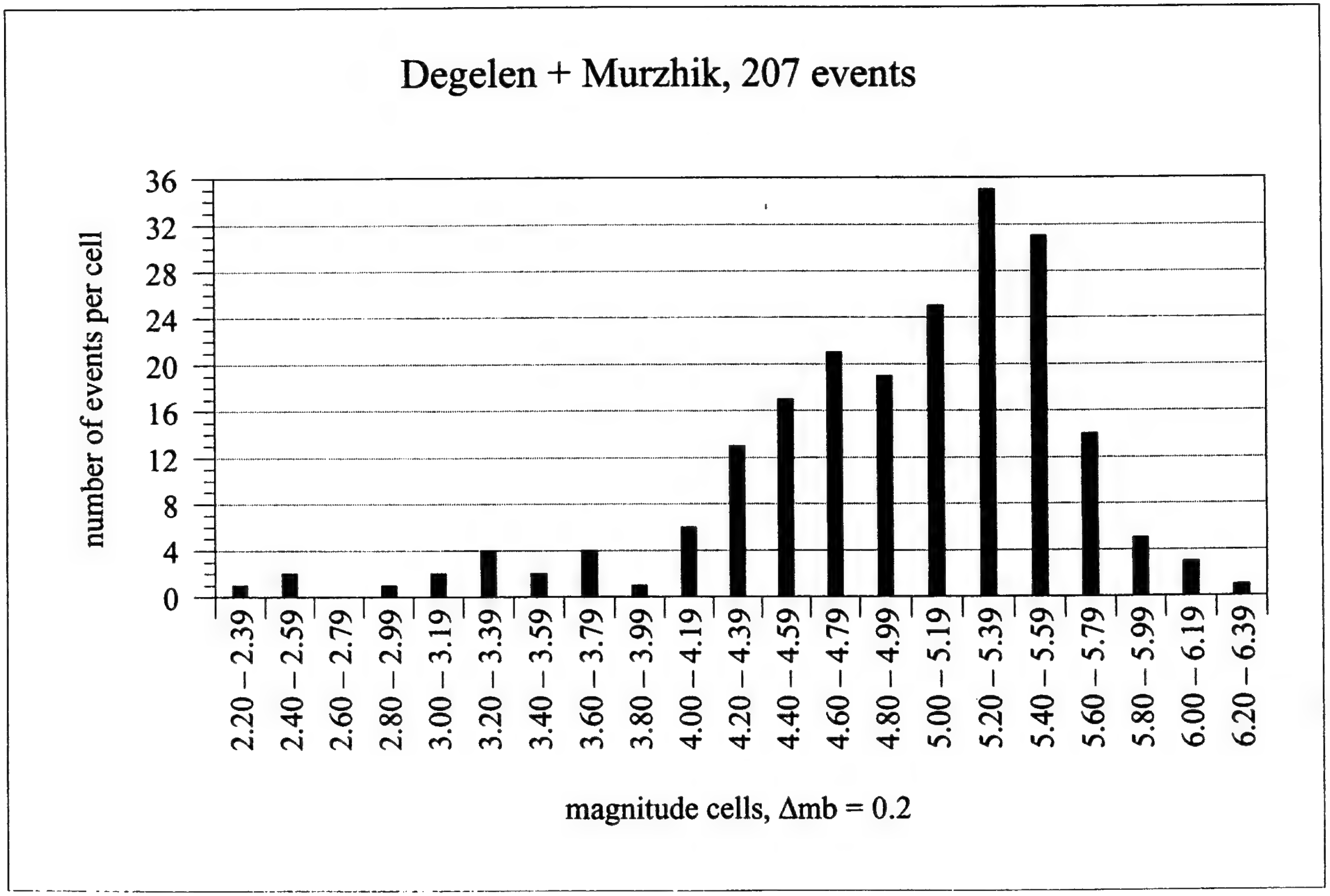
small magnitude UNEs which had not previously been reported in the open literature. But the price for these six detections was large, in that these authors also reported 39 events as UNEs which turned out to be false alarms, namely, 17 chemical explosions at STS, together with 15 chemical explosions in the Azgir region, 6 chemical explosions in different regions of the USSR, and one earthquake. The most important point to draw from this history is that detection capability has been very good for recent decades, since all but two UNTs at STS with yields announced as greater than 1 ton have now been associated with detections. Detections have also been very good using only teleseismic data. But for accurate location and confident identification, additional data is often needed. In practice, such additional data can often be provided by regional stations.

We conclude this section with Figure 7 showing the magnitude distribution for the Balapan region, and for the Degelen and Murzhik regions. Again, it is clear that Balapan was the preferred location for the largest tests, and Degelen for the smallest. Out of the total of 340 UNTs, more than 40 UNTs had $mb < 4.4$ and thus were probably sub-kiloton.



(a) Balapan sub-area.

Figure 7. Magnitude distribution for the Balapan region, and for the Degelen and Murzhik regions.



(b) Degelen and Murzhik sub-areas.

Figure 7. Magnitude distribution for the Balapan region, and for the Degelen and Murzhik regions (continued).

2.7 Conclusions.

We have found and analyzed regional seismic data for underground nuclear tests (UNTs) at the Semipalatinsk Test Site (STS) that enable us here (Table 8) to report the origin time and magnitude for 31 nuclear tests at this test site, that had not previously been documented in the open literature. Seismic detections for three of these UNTs were previously reported by Sykes and Ruggi (1986) and one by Ringdal (1990), but detections for the remaining 27 were not reported in the open literature before our study.

For 19 of these events we also obtained seismically-determined estimates of location, and location uncertainty. By comparison with ground truth location information that became available after our seismic determinations of location, we found that our location estimates were accurate to within a few km and our uncertainty estimates included the ground truth location in almost all cases. We conclude that regional waves can be used to provide accurate locations even when few stations are available, provided regional travel times are well calibrated.

There are only two UNTs at STS, announced as having yields greater than one ton, for which we have been unable to find detections. Both occurred in the 1960s.

Yield estimates based upon seismic magnitudes give values for the estimated total annual yield at that differ by less than 10% from officially announced values of these yield totals, for most of the last ten years of testing at the Semipalatinsk Test Site.

The information we have been able to report here, on 67 of the 69 UNTs that were previously not well documented, can be used to assess monitoring capability for this major nuclear test site and how that capability has improved with time. The information can also be used to identify small UNTs, and chemical explosions and earthquakes near STS, suitable for evaluation of methods of discriminating between small seismic events. We recommend that efforts be supported, to build up the database of regional waveforms for small seismic events on and near STS, since these are the types of waveform that monitoring programs must be designed to detect and identify.

Section 3

Infrasound Detection of Large Mining Blasts in Kazakstan

3.1 Introduction.

In order to meet the monitoring requirements of the Comprehensive Test Ban Treaty (CTBT), three technologies - seismic, hydroacoustic, and infrasonic - will be relied upon to detect acoustic waves produced by nuclear explosions detonated on land, in the sea, and in the air. While seismic and hydroacoustic technologies are sufficiently evolved to meet the monitoring needs of the CTBT, in its current state, infrasonic technology is not. There are several reasons why development of the infrasound component lags behind the other two. Chief among these is the greater difficulty encountered in recording acoustic signals in the atmosphere versus in the ocean or in the earth. The greater levels of cultural and flow noise in the atmosphere hinder reliable infrasonic detection. Detection can be improved by utilizing inlet hose or pipe arrays, designed to decorrelate wind noise by spatially filtering the input signal, however, there is much debate about the best configuration and material to use and today wind noise reduction remains an art.

Furthermore, temperatures in the atmosphere vary on time scales of hours to months, and wind speeds (up to 100 m/s) are a significant fraction of the average sound speed (~330 m/s). The result is that the acoustic propagation channels in the atmosphere are highly variable. This variability must be quantified for infrasonic monitoring to meet the needs of the CTBT. There is currently an acute lack of reliable infrasonic observations that can be utilized to examine the effects of time-dependent variations in atmospheric properties on the detectability and characteristics of infrasound signals. This is particularly true for infrasound generated from smaller explosions, which the CTBT aims to monitor, but which are likely to be recorded by only a few (1–3) of the nearest IMS stations.

Since October, 1997, we have conducted infrasound observations at the Kurchatov Geophysical Observatory in Kazakstan using available microphones coupled with existing noise reduction systems in order to address some of the infrasound monitoring issues outlined above. The Kurchatov Observatory (Figure 8) is an ideal site for research on infrasound and on the application of synergistic (seismic and acoustic) methods of event discrimination as it operates both a 21-element short-period seismic cross-array (Figure 9) and a three-component broadband seismic station, and because of its close proximity to several large (100+ ton) mining operations (Figure 8). In addition, conditions appear to be favorable for long-range infrasound propagation in Kazakstan, where infrasound signals have been detected out to 2,000 km distance [Al'Perovich et al., 1985].

Available noise reduction pipe arrays at the site are depicted in Figure 9. Three types of noise reduction configuration were utilized in this study: 1) six, 70 m long underground pipes extending radially from a central chamber and referred to as "East-" and "West-" spiders; 2) a

single, 30 m long pipe with an outlet at the center of the length; and 3) an "H-pipe" array consisting of two, 300 m long pipes joined at their centers by a 100 m long pipe (Figure 9). The 300 m long pipes are raised 1 m above the ground and have sampling nozzles spaced at 3 m intervals located on their undersides, facing the ground. The internal diameter of the 300 m long pipes varies from 1/2 inch at the ends to 2 inches in the middle. The 30 m long pipe is raised 0.5 m above the ground and has sampling nozzles spaced at 0.5 m intervals. We presume that these systems, which were constructed during the Soviet era, were designed to be functional during the severe local winters, when snow covers the ground for five months each year and prohibits the use of conventional plastic hoses. Transfer functions for these systems are not yet determined.

Two types of capacitor microphone - Globe and Soviet K301 - have been utilized with the pipe arrays described above. Globe microphones have been used widely in infrasound research for many years and their broadband response is well known (e.g., Donn and Posmentier [1968]). The K301s were originally installed at Kurchatov in the early 1970's by the Russian Ministry of Defense and recorded on paper. It is noteworthy that the recording site is only about 1400 km from the Chinese nuclear test site at Lop Nor, where some 12–13 atmospheric nuclear tests were conducted in the 1970s and one (the last) in 1980. Since February, 1995, the analog signal from a K301 sensor has been digitized and recorded by a 16-bit A/D system together with the seismic channels from the 21-element bore-hole, short-period (0.5-5.0 Hz) vertical seismic array. The K301 microphone has variable gain (mv/Pa) and has exceptionally good sensitivity to longer periods (.01-0.3 Hz). Since October, 1997, 4–8 microphones connected to the various noise reduction systems have been simultaneously recorded.

3.2 Observations.

Several large mines in the region generate explosions that are routinely detected seismically and, in some cases, are also detected with infrasound. The mines range in distance from 80 to 750 km from the infrasound array. The Ekibastuz mine, 250 km NW of the array, regularly produces 4–6 seismic detections per day. However, associated infrasonic detections are found only for roughly 10% of the events. Between October 1997 and January 1998, we detected infrasound signals generated by 26 Ekibastuz events. The location and origin time of each event were determined from the seismic cross-array and are listed in Table 11. Ekibastuz comprises a number of coal mines centered about (51.67N, 75.40E) as determined by satellite photographs [Thurber et al., 1990].

The infrasound wavetrain generated by Ekibastuz explosions can be classified into two different types. The first type, shown in Figure 10, consists of 1 or 2 simple pulses, with travel times of approximately 740 and 810 s with respect to the seismically estimated origin time. The second arrival is observed in about 60% of the events (18) from Ekibastuz; when the second arrival is present, it generally follows the first by 50-70 s, though this can range anywhere from 24 to 85 s (Table 11). The travel time of the first arrival exhibits great variation and probably reflects varying atmospheric conditions such as transient propagation ducts. This is discussed further in the next section.

Figure 8. Map of Kazakstan and central Siberia showing locations of broadband seismic stations in Kazakstan (solid traingles), active mining areas (diamonds), Kuzbass and Abakan mining areas (shaded squares), the Balapan nuclear test site (star), and the Kurchatov Geophysical Observatory (KUR), where the seismic and infrasonic observations were made.

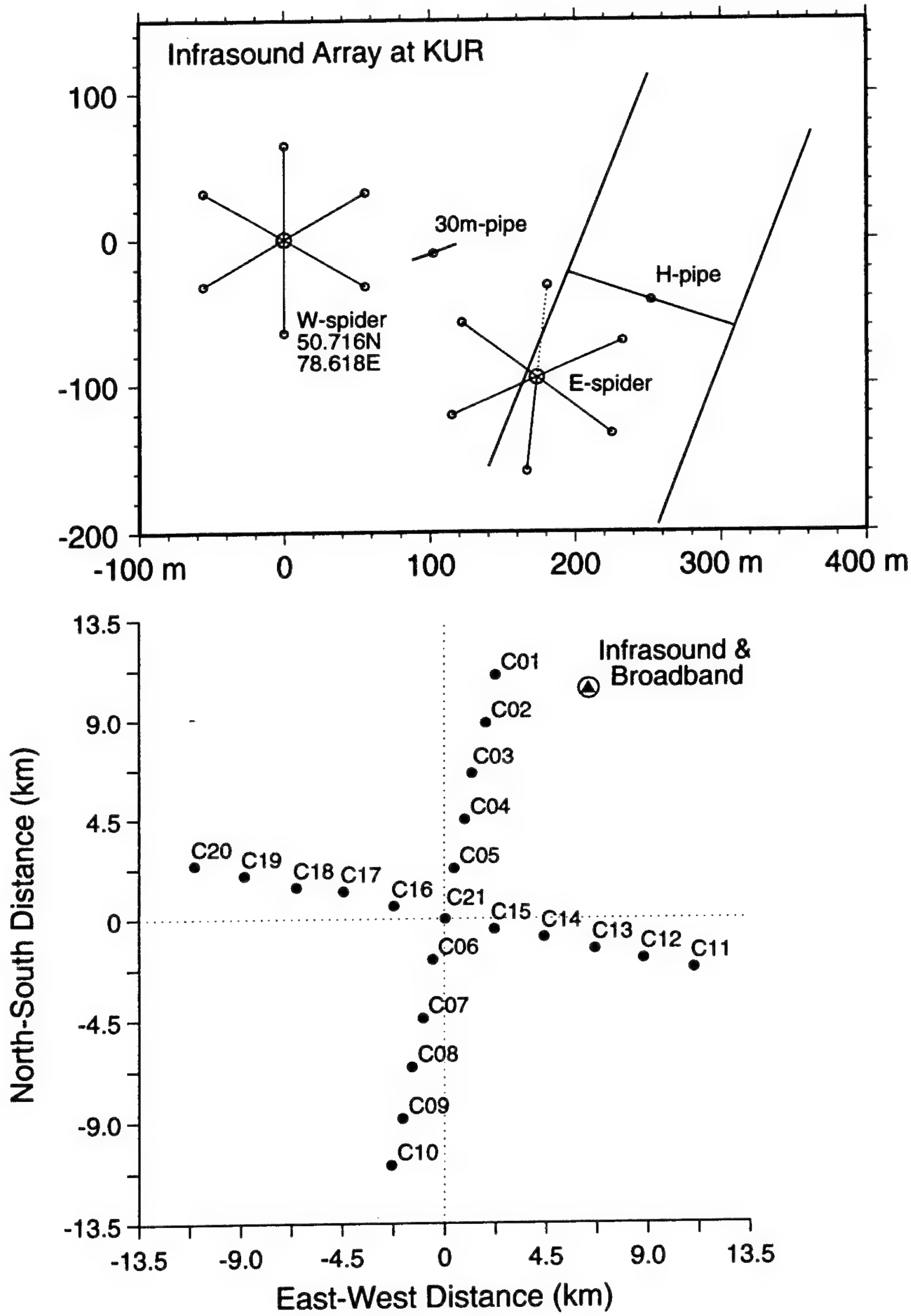


Figure 9. Top panel: Infrasound noise reduction systems (pipe arrays) utilized in this study. All are located within the Kurchatov Geophysical Observatory compound, which also houses the central recording unit for the cross array and a three-component broadband seismometer installed in a 25 m shaft. Bottom panel: Plan view of the 21-element seismic borehole array (cross array) at Kurchatov and location of infrasound sensors.

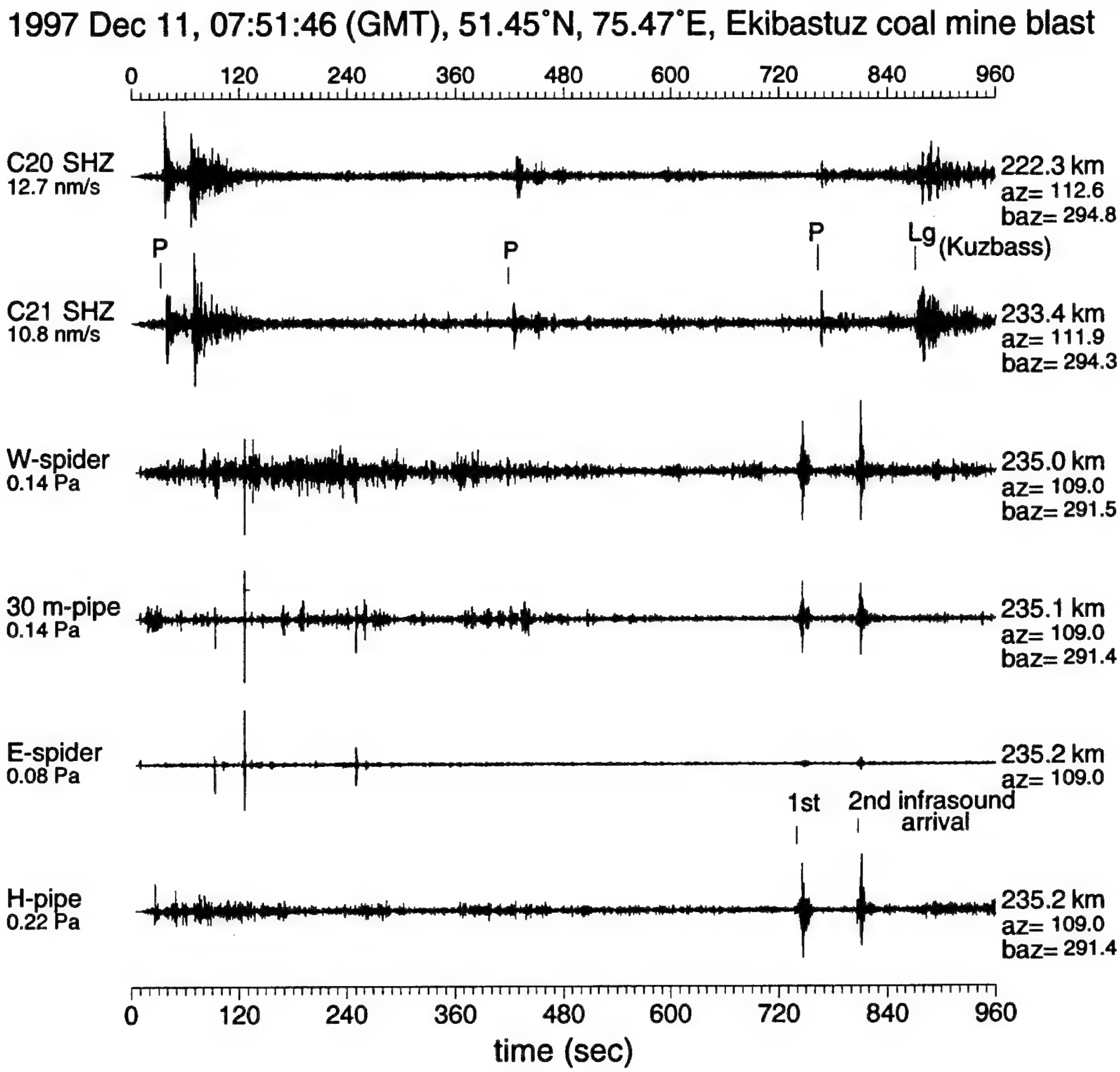


Figure 10. Selected cross-array seismic channels (top two traces) and infrasound signals recorded with four different noise reduction systems (Figure 2) for an Ekibastuz coal mine blast on Dec. 11, 1997.

Table 11. **List of infrasound signals from mining blasts at Ekibastuz, Kazakstan**

Id no.	Origin time mo/da/year	Origin time hh:mm:sec	Magnitude	Phase id	Travel time (s)	Group velocity (m/s)	Amplitude (Pa)
01	10/16/1997	08:16:13	2.1	S1	820	303	0.22
02	10/16/1997	08:28:43	2.6	S1	810	307	0.23
03	10/16/1997	08:34:39	2.3	S1	825	301	0.11
04	10/17/1997*	11:39:14	2.2	S1	646	325	0.13
				S2	731	287	0.06
05	11/19/1997	09:37:57	2.2	S1	730	341	0.09
06	11/19/1997	10:20:07	2.5	S1	793	313	0.13
07	11/27/1997	07:43:17	2.2	S1	763	326	0.29
08	11/27/1997	09:47:45	1.9	S1	788	315	0.16
09	11/27/1997	09:53:18	2.4	S1	765	325	0.54
10	11/28/1997	08:34:14	2.5	S1	763	326	0.13
11	11/28/1997	08:58:06	2.4	S1	761	327	0.19
12	11/28/1997	09:30:49	2.3	S1	757	328	0.45
13	12/02/1997	08:48:11	1.9	S1	734	339	0.29
				S2	793	313	0.17
14	12/02/1997	09:23:38	1.6	S1	756	329	0.08
				S2	794	313	0.05
15	12/02/1997	09:27:25	2.0	S1	746	333	0.41
				S2	786	316	0.22
16	12/02/1997	10:29:01	2.1	S1	743	335	0.13
				S2	779	319	0.08
17	12/11/1997	07:51:46	2.4	S1	739	336	0.23
				S2	809	307	0.29
18	12/11/1997	07:57:43	1.9	S1	718	346	0.04
				S2	799	311	0.03
19	12/11/1997	08:36:50	2.8	S1	747	333	0.09
				S2	809	307	0.05
20	12/11/1997	08:58:22	2.5	S1	750	332	0.19
				S2	812	306	0.17
21	12/11/1997	10:49:47	2.2	S1	737	337	0.09
				S2	798	312	0.06
22	01/14/1998	07:02:34	2.0	S1	796	312	0.26
				S2	827	301	0.49
23	01/14/1998	08:13:40	2.4	S1	795	313	0.26
				S2	829	300	0.31
24	01/14/1998	09:16:47	2.6	S1	815	305	0.17
25	01/28/98	07:31:04	3.0	S1	753	330	0.15
26	01/28/1998	08:15:21	2.4	S1	764	325	0.25

The second type of infrasonic wavetrain associated with Ekibastuz events, shown in Figure 11a, consists of a series of pulses of growing amplitude lasting some 20–30 s. The event shown in Figure 11a is actually two explosions closely spaced in time. While the seismic waves from the two explosions overlap, making it difficult to resolve two events, the lower phase velocities and shorter durations of the infrasonic waves allow the two events to be distinguished (Figure 11b). For this reason, infrasound observations may be crucial for detecting a shallow nuclear test hidden in the seismic coda of an earlier event. There is no evidence for multiple cast firing within either of the two seismic events, hence, the multiple phases observed in the infrasound data must be produced by propagation effects. This is discussed further in the next section.

During the observation period, three infrasound signals from events in the Kara-Zhyra coal mine in the Balapan former Soviet nuclear test site were identified (Table 12). Figure 12 shows seismic and infrasonic signals originating from one such event, located 80 km S of Kurchatov. Peak infrasound pressure is about 0.35 Pa and there is some evidence of dispersion; the period of the initial arrival is 0.85 s and gradually decreases to 0.37 s.

3.3 Modeling.

In order to identify the infrasound arrivals, we ray traced through various suitable atmospheric models. Figure 13a shows the sound speed (c) as a function of height in the atmosphere derived from mid-latitude (45N) temperature profiles for January and July [Valley, 1965] and the well-known theoretical relation $c(T) = 20.1\sqrt{T(K)}$, where T is the temperature in degrees Kelvin. Above 130 km, average sound speeds from the 1962 U.S. Standard Atmosphere have been used. In Figure 13b mid-latitude zonal wind models for summer and winter adapted from Georges and Beasley [1977] are shown, along with wind profiles measured by the high-resolution Doppler imager aboard the Upper Atmosphere Research Satellite (UARS) [Flemming et al., 1996]. While the details vary among the models, both display the prominent seasonal shift in stratospheric wind direction; at 50–80 km, strong summer easterlies give way to winter westerlies. This has an important effect on the seasonal reception of infrasound. Figure 13c shows mid-latitude meridonal wind models taken from Georges and Beasley [1977]; the meridonal winds are smaller than the zonal winds at altitudes less than 100 km and therefore have less impact on infrasound propagation. Figure 14 presents the results of ray tracing through a sound-speed profile given by the mid-latitude winter temperature profile alone, neglecting the effects of wind. As can be seen, in this high-frequency ray approximation, no energy is predicted to return to the earth surface at distances less than 280 km. Beyond 280 km, the first arrivals turn in the thermosphere, at altitudes of $\sim$150 km, followed by secondary arrivals that turn at $\sim$125 km; no energy is returned from the stratosphere (40–80 km). Thus, in the absence of wind, no favorable propagation paths exist between Ekibastuz and Kurchatov (Δ=250 km). In order to correctly compute the predicted ray paths and travel times through the atmosphere, we must consider both the temperature and wind effects on the resulting sound speed. Several past studies have combined the temperature-derived sound speed, $c(z)$, and the component of horizontal wind velocity along the propagation path, $w'(z)$, into an effective sound-speed profile for a given propagation azimuth, $v(z) = c(z) + w'(z)$, that can be used, along with Snell's law, to compute ray paths and travel times. Here the effective wind speed along the propagation

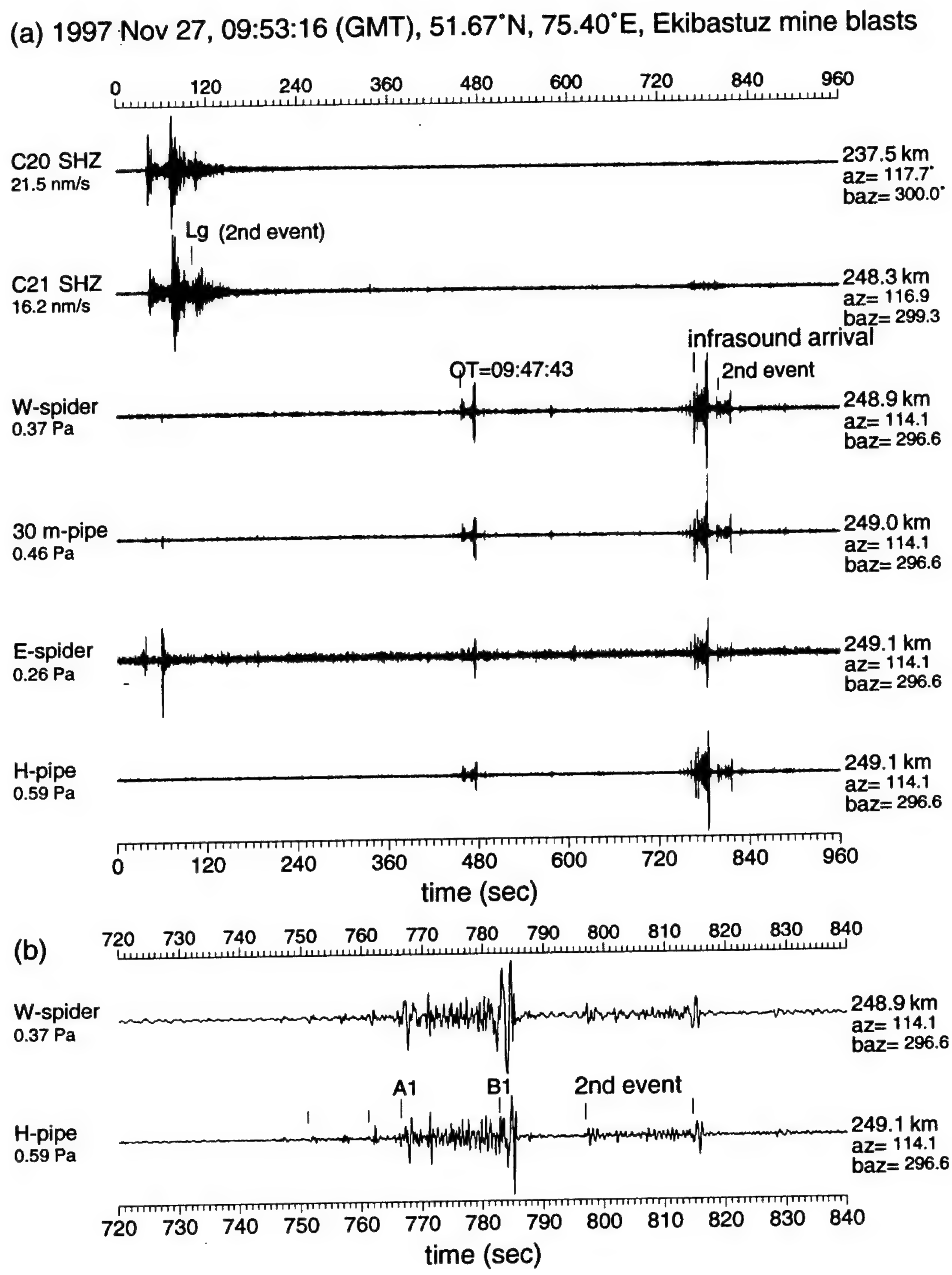


Figure 11. (a) Same as Figure 10 for Ekibastuz mine blast on Nov. 27, 1997. This event is actually two closely spaced explosions which produce overlapping Lg phases in the seismic channels but produces separate infrasound arrivals. An additional infrasound arrival at t~460 s is from an earlier Ekibastuz event. (b) Blow up of the infrasound signals shown in (a). Each event is seen to consist of a sequence of pulses of increasing amplitude lasting 20-30 s.

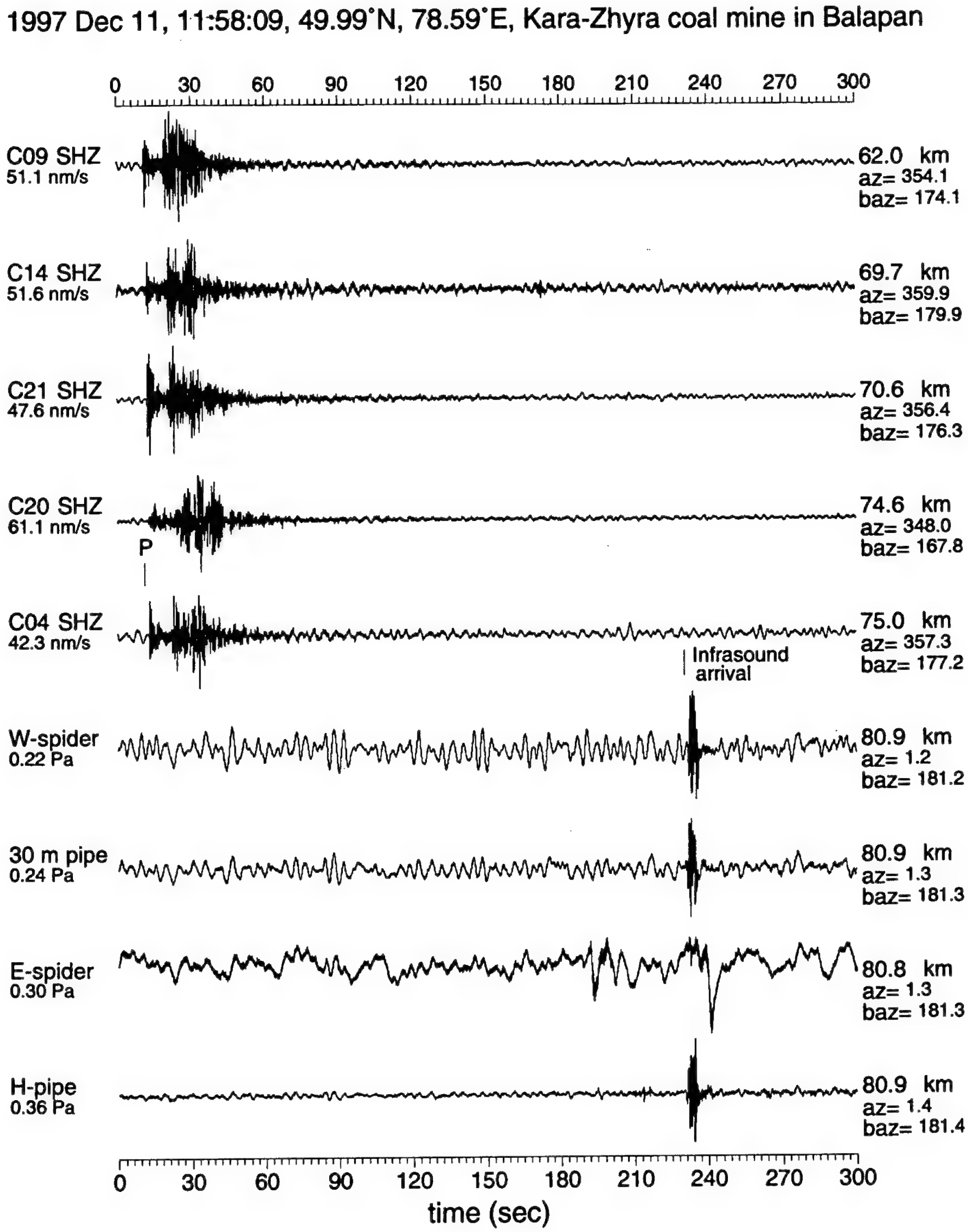


Figure 12. Selected cross-array seismic channels (top five traces) and infrasound signals recorded with four different noise reduction systems (Figure 9) for an event located in the Kara-Zhyra coal mine in Balapan, some 80 km south of Kurchatov, on Dec. 11, 1997.

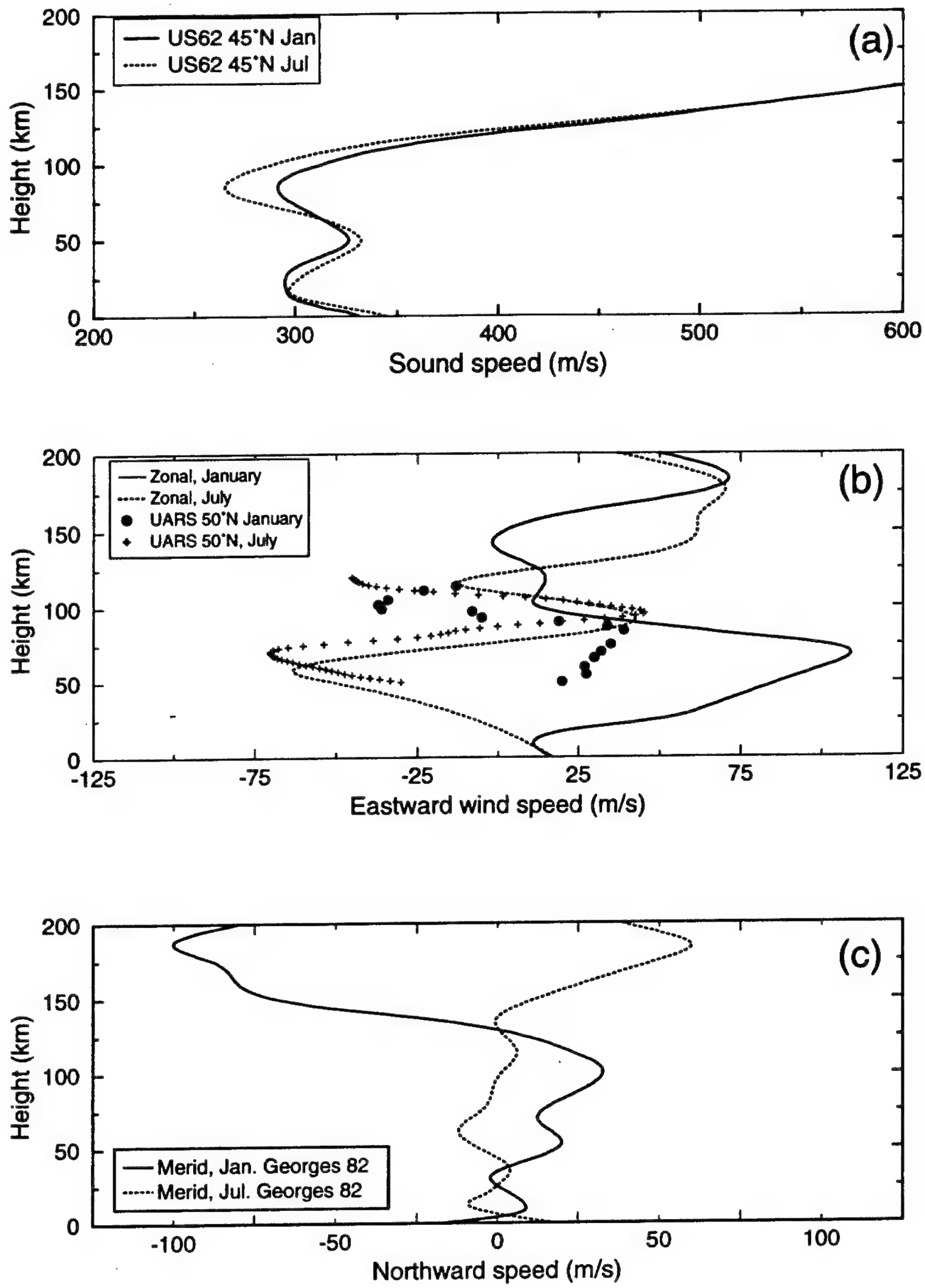


Figure 13. (a) January and July sound-speed profiles derived from the 1962 U.S. Standard Atmosphere midlatitude (45N) temperature profiles [Valley, 1965]. (b) January and July midlatitude zonal winds taken from Georges and Beasley [1977]. Also shown for comparison are zonal winds measured by the high-resolution Doppler imager aboard the Upper Atmosphere Research Satellite (UARS) [Fleming et al., 1996]. (c) January and July midlatitude meridonal winds from Georges and Beasley [1977].

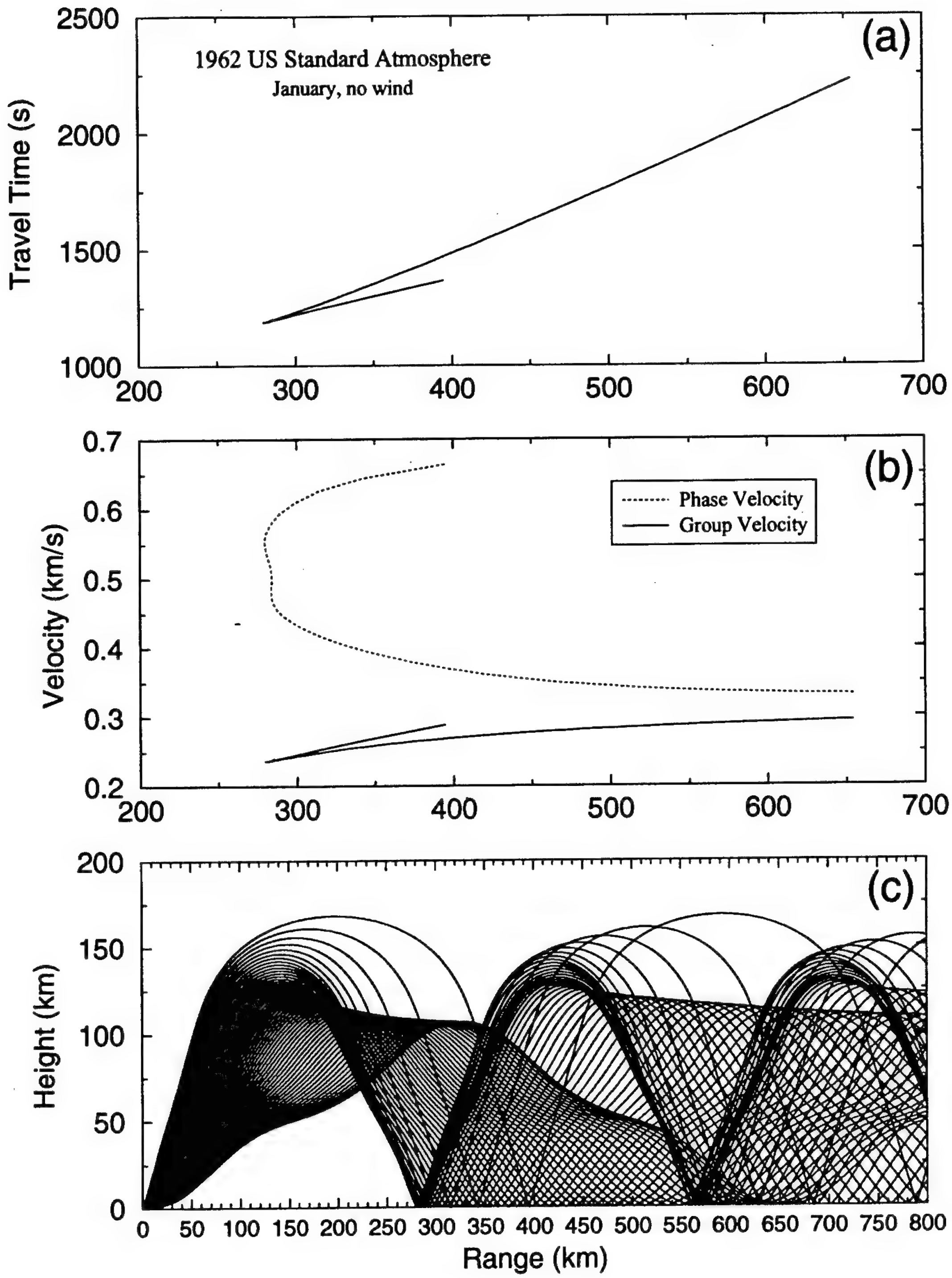


Figure 14. Results of ray tracing through a sound speed profile given by the 1962 U.S. Standard Atmosphere midlatitude temperature profile for January, neglecting wind. (a) Travel time curve. (b) Group and phase velocity curves. (c) Raypaths for take-off angles of 30–90°.

Table 12. **List of infrasound signals from other mining blasts**

Id	Origin time mo/da/year	hh:mm:sec	Lat. (°N)	Long. (°E)	Mag	Phase id	TT (s)	Group velocity (m/s)	Amp (Pa)
				Novotaubinka near Semipalatinsk					
1	11/19/1997	09:24:38	49.80	80.85	0.5	D	624	302	0.10
				Kara-Zhyra mine in Balapan					
1	11/19/1997	10:28:27	50.01	78.80	3.7	D	252	317	0.58
2	12/11/1997	11:58:10	49.99	78.59	1.8	D	232	234	0.39

Mag = magnitude, TT = travel time, Gv = group velocity in km/s, Amp = amplitude in Pa.

azimuth is $w'(z) = w \times cos(W_d - az)$, where w is the wind magnitude, and W_d and az are the wind direction and the receiver azimuth in degrees measured clockwise from north. Thus, the horizontal wind enhances sound propagation in the wind direction (downwind) and retards it in the opposite direction (upwind).

However, as noted by Thompson [1971] and recently by Garcés et al. [1998], the above is an approximate treatment of sound propagation in a moving medium, and is not strictly correct. A more correct treatment is obtained by ray tracing in a coordinate frame that is moving at the wind velocity. It is still convenient to rotate the wind vector $\vec{u}$ with respect to the receiver azimuth, $\vec{u} = u(z)\hat{i_x} + v(z)\hat{i_y}$, where $u(z)$ and $v(z)$ are the wind components parallel and transverse to the receiver azimuth, respectively. Raypaths computed using the effective speed and the 'correct' wind treatment are compared in Figure 15 for take-off angles of 45°and 85°. While the rays still turn at a height where the effective speed equals the horizontal phase velocity at the surface, the horizontal distance where this occurs is different for the two methods. Figure 16 compares the travel-time, phase velocity, and group velocity curves that result from using the two different methods to ray trace through the winter temperature and wind models (Figure 13). While the travel-time and group velocity curves are indistinguishable, the phase velocity curves are offset horizontally. This will have important implications for CTBT monitoring, as the error in location derived from the phase velocity obtained from ray-tracing with the effective speed may be as large as 25–40 km for the thermospheric returns, and will increase with increasing numbers of ray bounces (Figure 15). However, for our present needs, which are to identify the observed infrasound phases, the effective sound speed method is adequate and is used hereafter. Figure 16c shows that the first rays arriving at 220–250 km have turned in the stratosphere (h$\sim$38 km). The predicted travel time and phase velocity match the observed values at Ekibastuz reasonably well, however, the second observed arrival is not predicted by this model. In order to produce two arrivals with the observed time separation ($\sim$70 s) at Δ=250 km, a tropospheric duct must exist between Ekibastuz and Kurchatov. This is supported by the observation of a direct (tropospheric) arrival from Kara-Zhyra explosions,

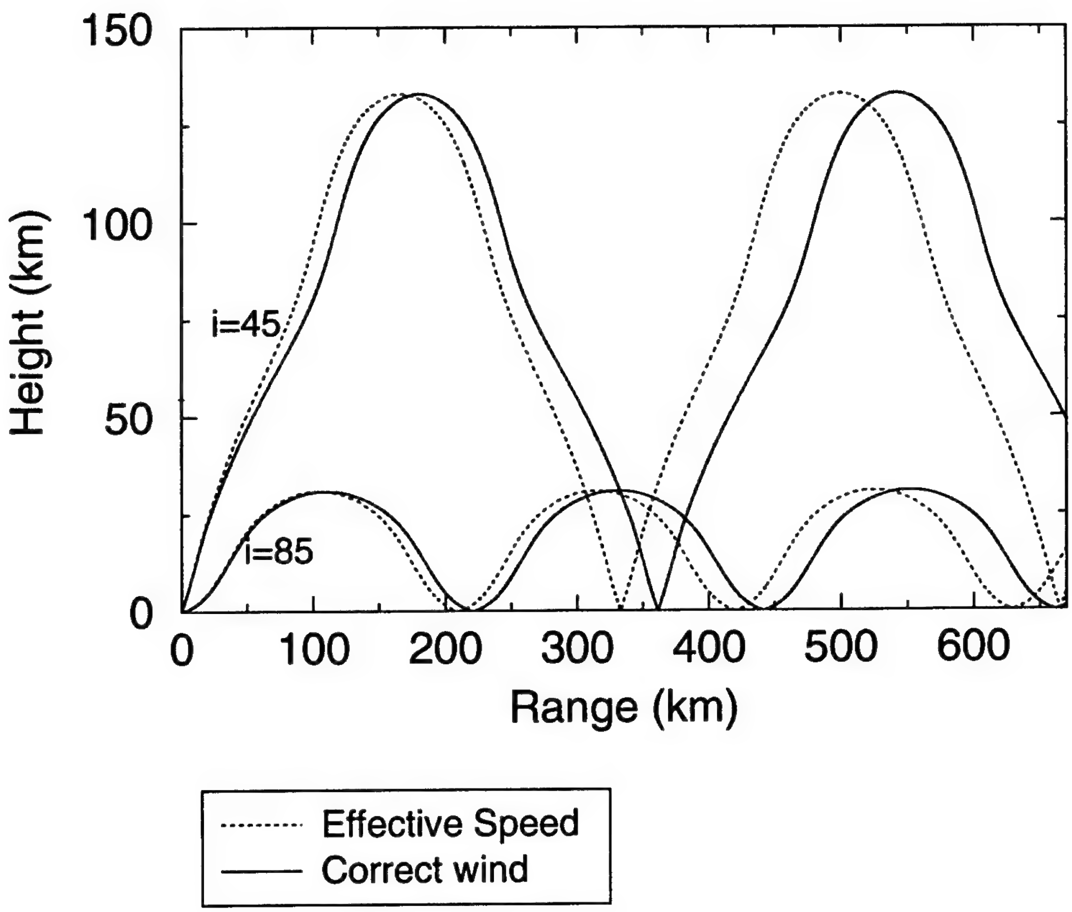


Figure 15. Comparison of raypaths computed using the effective speed method (solid line) and a method that includes the wind speed in the ray equations (dotted line). For both cases, the sound-speed model used is the same as in Figure 14, and the wind model used is the projection of the mid-latitude wind model of Georges and Beasley [1977] (Figure 13) in the direction of the azimuth from Ekibastuz to Kurchatov. Rays are compared for take-off angles of 45° and 85° from vertical.

80 km away and well within the shadow zone predicted by models with no tropospheric duct (Figure 16). The existence of a tropospheric duct implies an increase in the effective sound speed between the surface and the tropopause (0–15 km); we cannot distinguish whether this is caused by a temperature inversion or a westerly jet, however, we prefer the former as the duct must exist in both the easterly and northerly directions. Support for a temperature inversion can be found in a study on infrasound reception of explosions detonated at 1 km height in the atmosphere in southern Kazakstan during winter [Al'Perovich et al., 1985]; direct arrivals observed out to distances of 200 km were linked with meteorological measurements in the troposphere that confirmed a temperature inversion between the surface and 2–4 km.

A modified sound-speed profile which contains a favorable tropospheric duct is presented in Figure 17 along with the resulting travel-time and velocity curves. For this model, the first arrival at 250 km propagates through the tropospheric duct and is followed some 70 s later by a stratospheric arrival. The modified tropospheric profile results in good matches to the observed first arrival travel times at 80 and 250 km (Figure 17c). It proved very difficult to find a model that would predict two arrivals at a distance of 250 km separated by such a large amount of time (70 s). While the model shown in Figure 17 is by no means unique, only models with a fast troposphere and an elevated stratospheric lid were able to match the observed arrival times (Figure 17a, inset). More conservative modifications to the winter models (Figure 16) which consisted of increasing the sound-speed gradient in the troposphere and stratosphere succeeded in producing several arrivals at a range of 250 km, however, all arrived within a time window of about 20 s. This suggests that the multiple arrivals observed for the second type of infrasound signals (Figure 11b) likely result from strong tropospheric and stratospheric gradients.

As shown by Garcés et al. [1998], the effect of the transverse wind component is to translate the ray coordinate frame a distance Δy perpendicular to the original wave normal direction. This will not affect the ray parameter, but it will affect the back-azimuth measured at the array. However, both synthetic modeling [Garcés et al., 1998] and observations [Georges and Beasley, 1977], suggest that this deviation will be less than 10°for realistic wind models. In particular, since the dominant winds are zonal (E-W) and since the back-azimuth from Kurchatov to Ekibastuz is nearly E-W, the deviation should be quite small. Hence, the discrepancy between the observed and predicted back-azimuths for Ekibastuz arrivals is likely due to the poor azimuthal resolution of the array, resulting from the small sensor separation.

3.4 Discussion.

We have presented here an initial interpretation of the characteristics of infrasound propagation observed in northern Kazakstan. The infrasound signals associated with Ekibastuz events can be classified into two types. The first type consists of two pulses spaced 50–70 s apart, while the second type consists of multiple pulses arriving within about a 20–30 s window. Infrasound arrivals from both Ekibastuz (Δ=250 km) and Kara-Zhyra(Δ=80 km) explosions support the existence of a tropospheric duct, produced by a temperature inversion and/or a westerly jet in the troposphere. The multiple arrivals characteristic of the second type of infrasound wavetrains likely result from strong positive sound speed gradients in the troposphere and, especially, in the

upper stratosphere. The large variability in the character of infrasound signals generated by Ekibastuz events over short time scales (hours to days) is indicative of the rapidity of atmospheric fluctuations.

In the absence of wind, no favorable propagation ducts exist between Ekibastuz and Kurchatov. This may explain the low detection rate (10%) of infrasound signals from Ekibastuz events. Indeed, there is some evidence that the infrasound detectability is seasonal, with greater numbers of detections occurring during the winter months (Table 11), when westerly winds create a strong stratospheric duct between Ekibastuz and Kurchatov. Since the dominant stratospheric winds are zonal (E-W), a seasonal dependence of infrasound detectability of Ekibastuz (Baz=297°) explosions should be observed. However, it is also possible that periods of low detection coincide with high surface winds at the receiver which mask infrasound reception. In fact, we do find some evidence for low infrasound detectability when surface winds exceed about 1.7 m/s and we are investigating this possibility further. Finally, infrasound detection could be affected by variable coupling between the seismic and acoustic wavefields at the source.

Measurements of the back-azimuth of different infrasound arrivals have the potential to resolve some of the ambiguity that exists in using infrasound to infer the horizontal wind structure in the atmosphere. However, much more accurate back-azimuth estimates than can be obtained by a small aperture array are required. For this reason, we have extended the small array at Kurchatov into a larger triangular array with 2 km sides. In addition, we intend to install a second three-element infrasound array at Borovoye, 377 km NW of Ekibastuz (Figure 8), in order to examine the seasonal effects of the stratospheric winds both upwind and downwind from the source. We hope that these improved infrasound arrays will provide unique data that may be used to advance the infrasound technology used for CTBT monitoring.

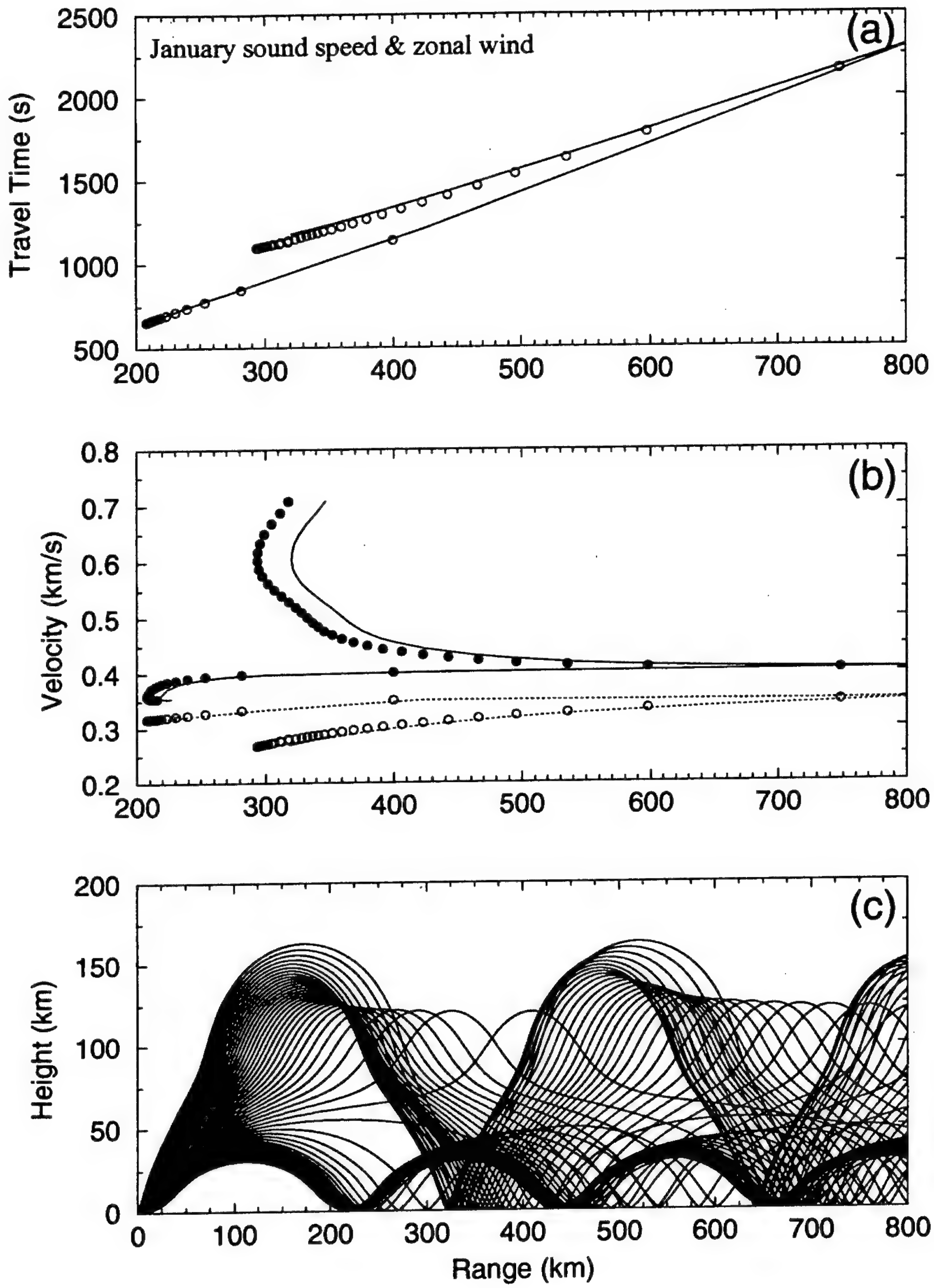


Figure 16. Results of ray tracing through a sound speed profile given by the 1962 U.S. Standard Atmosphere midlatitude temperature profile and the January zonal wind model. Solid and dotted lines correspond to the exact wind treatment, open and filled circles correspond to the approximate (effective speed) method. a) Travel times. b) Phase (solid line and filled circle) and group (dotted line and open circle) velocities. c) Ray paths computed for the exact method.

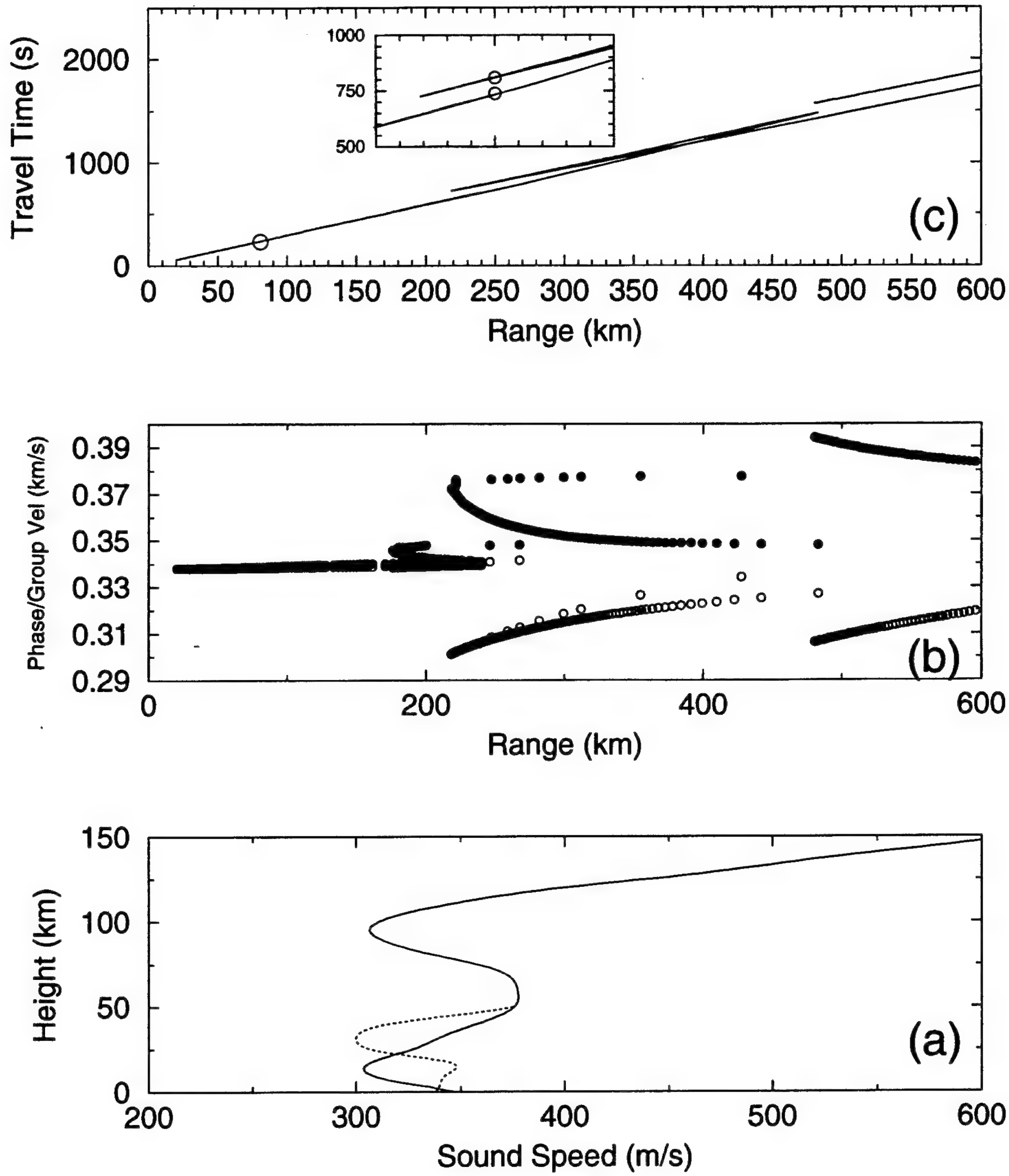


Figure 17. a) Effective sound speed profiles computed for a winter model (solid line) and modified below 50 km (dotted line). b) Phase (filled circles) and group (open circles) velocity curves for the modified model shown in a). c) Travel-time curve for the modified model shown in a). Also shown are the infrasound arrival times observed at Kurchatov from Balapan (Δ=80 km) and Ekibastuz (Δ=250 km) (inset) events.

Section 4

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